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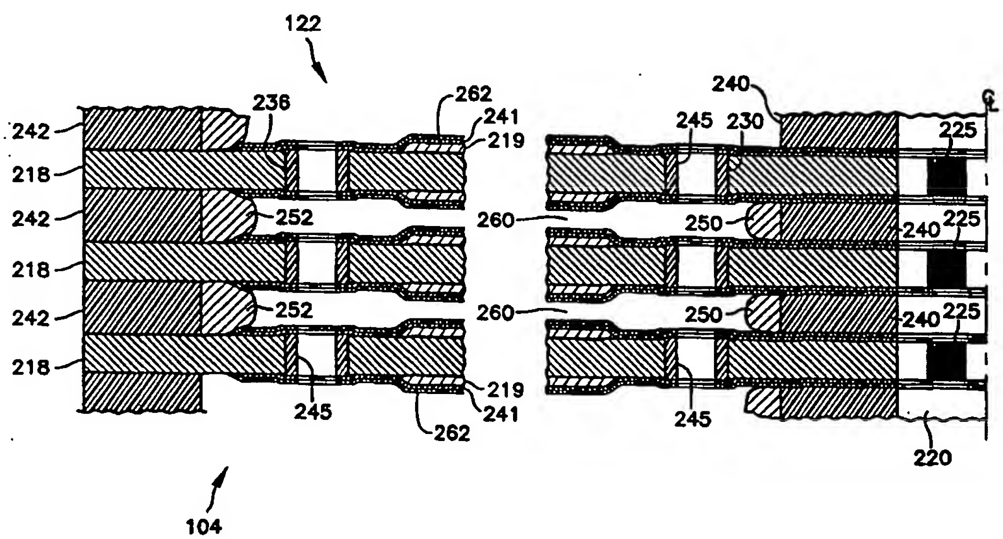

(57) Abstract

A vibratory separation system has a drive mechanism for imparting a vibratory motion to a membrane module to enhance filtration. The membrane module comprises one or more filter elements arranged in a stack, each filter element having a separation medium. The vibratory motion imparted to the membrane module generates a dynamic flow boundary layer at the separation media. This fluid shear boundary layer, in turn, generates lift, thereby inhibiting fouling of the separation media.

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SEPARATION SYSTEMS, MEMBRANE MODULES, FILTER ELEMENTS AND METHODS FOR MAKING FILTER ELEMENTS

This application claims the priority of U.S. provisional patent application 60/071,843, filed January 20, 1998, and U.S. provisional patent application 60/072,040, filed January 21, 1998, which applications are incorporated by reference in their entirety. This application also incorporates by reference the disclosure of International Publication No. WO 97/02087, entitled "Separation Systems and Methods.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to vibratory separation systems, membrane modules, filter elements, and other components that may be used in a vibratory separation system and methods for making filter elements that may be used in a vibratory separation system.

2. Description of the Related Art

Separation devices are typically utilized to separate one or more components of a fluid from other components in the fluid. As used herein, the term "fluid" includes liquids, gases, and mixtures and combinations of liquids, gases and/or solids. A wide variety of common processes are carried out in separation devices, including, for example, classic or particle filtration, microfiltration, ultrafiltration, nanofiltration, reverse osmosis (hyperfiltration), dialysis, electrodialysis, prevaporation, water splitting, sieving, affinity separation, affinity purification, affinity sorption, chromatography, gel filtration, bacteriological filtration, and coalescence. Typical separation devices may include dead end filters, open end filters, cross-flow filters, dynamic filters, vibratory separation filters, disposable filters, regenerable filters including backwashable, blowback and solvent cleanable, and hybrid filters which comprise different aspects of the various above described devices.

Accordingly, as used herein, the term "separation" shall be understood to include all processes, including filtration, wherein one or more components of a fluid is or are separated from the other components of the fluid. The term "separation medium" shall be

understood to include any medium made of any material that allows one or more components of a fluid to pass therethrough in order to separate those components from the other components of the fluid. The terminology utilized to define the various components of the fluid undergoing separation and the products of these processes may vary widely depending upon the application, e.g., liquid or gas filtration, and the type of separation system utilized, e.g., dead end or open end systems; however, for clarity, the following terms shall be utilized. The fluid which is input to the separation system shall be referred to as process fluid and construed to include any fluid undergoing separation. The portion of the fluid which passes through the separation medium shall be referred to as permeate and construed to include filtrate as well as other terms. The portion of the fluid which does not pass through the separation medium shall be referred to as retentate and construed to include concentrate, bleed fluid, as well as other terms.

A common problem in virtually all separation systems is blinding or fouling of the separation medium, such as a permeable membrane. Permeate passing through the separation medium from the upstream side to the downstream side of the separation medium leaves a fluid layer adjacent to the upstream side of the separation medium having a different composition than that of the process fluid. This fluid layer may include components which bind to the separation medium and clog its pores, thereby fouling the separation medium, or may remain as a stagnant boundary or gel layer, either of which hinders transport of the components trying to pass through the separation medium to the downstream side of the separation medium. In essence, mass transport through the separation medium per unit time, i.e., flux, may be reduced and the inherent sieving or trapping capability of the separation medium may be adversely affected.

In certain separation systems, it is well known that if the separation medium and the layer of fluid adjacent to the surface of the separation medium are moved rapidly with respect to each other, fouling of the separation medium is greatly reduced. Accordingly, the life of the separation medium is prolonged and permeate flow rate is improved.

In vibratory separation systems, the process fluid and the separation medium are moved rapidly with respect to each other by rapidly oscillating the filter elements back and forth while the filter elements are in contact with the process fluid. For example, in the vibratory separation systems described in International Publication No. WO 97/02087, several generally circular filter elements are stacked to form a membrane module and the

membrane module is rapidly oscillated by a drive mechanism. Process fluid is supplied to the vibrating membrane module and retentate and permeate are removed from the vibratory membrane module through various openings in the filter elements.

While the vibratory separation systems described in International Publication No. WO 97/02087 have performed remarkably well, various aspects of these systems bear further consideration. For example, each filter element comprises one or more porous layers bonded to a support plate. As process fluid, retentate, and permeate flow through the various holes in the porous layers and the support plate, it is important to effectively seal the process fluid and the retentate from the permeate to prevent contamination of the permeate. Further, because the filter elements are rapidly vibrated while they are in contact with the process fluid, it is important to securely bond the porous layers to the support plate to prevent damage to the filter elements. In addition, because the filter elements may be recurrently replaced, it is important to provide a filter element which is economical as well as highly effective.

SUMMARY OF THE INVENTION

The vibratory separation systems, membrane modules, and filter elements, as well as the methods for making filter elements, which embody the various aspects of the invention provide many advantages over conventional vibratory separation systems and components.

In accordance with one aspect of the invention, a filter element includes a support plate having at least one through hole, a separation medium mounted on the support plate, and a sealing member disposed at the hole to prevent fluid from flowing from the hole between the support plate and the separation medium.

Filter elements embodying this aspect of the present invention are highly reliable and effective in preventing leakage between the separation media and the support plates. The sealing members can be securely attached to the separation media and the support plates. And if the bonding layers are present in the vicinity of the through holes of the support plates, the sealing member can fill the interstices in the bonding layers, preventing leakage through the bonding layers between the separation media and the support plates. In addition, the sealing members result in the separation media having a very smooth surface surrounding the process fluid holes or retentate holes, so filtering conditions are

improved.

In accordance with yet another of the invention, a filter element includes a support plate, a separation medium mounted on the support plate, a drainage layer disposed between the separation medium and the support plate, and a bonding layer disposed between the separation medium and the drainage layer.

In accordance with still yet another of the invention, a filter element includes a support plate, a separation medium mounted on the support plate, a drainage layer disposed between the separation medium and the support plate, and a bonding layer disposed between the support plate and the drainage layer.

In accordance with a further aspect of the invention, a filter element includes a support plate, a separation medium mounted on the support plate and having an inner portion, an intermediate portion and an outer portion, a drainage layer disposed between the separation medium and the support plate in the intermediate portion of the separation medium, and a bonding layer disposed between the separation medium and the support plate in the inner portion of the separation medium to bond the separation medium to the support plate.

Filter elements embodying these aspects of the present invention provide separation media and/or drainage layers which are securely and reliably mounted to support plates. The bonding layer used in embodiments of the present invention can effectively and reliably bond a separation medium to a drainage medium or a support plate, or a drainage medium to a support plate. The use of the bonding layers greatly simplifies the manufacturing of a filter element, allowing, in most cases, several layers of separation and drainage media to be attached to a support plate in a single step of operation.

In accordance with a still further aspect of the invention, a filter element includes a support plate, a separation medium mounted on the support plate and having an inner portion, an intermediate portion and an outer portion, a drainage layer disposed between the separation medium and the support plate in the intermediate portion of the separation medium, and a bonding layer disposed between the separation medium and the support plate in the outer portion of the separation medium to bond the separation medium to the support plate.

In accordance with another aspect of the invention, a filter element includes a

support plate, a separation medium mounted on the support plate, and a drainage layer disposed between the separation medium and the support plate. The drainage layer has a thickness less than about 0.6 mm.

In accordance with still another aspect of the invention, a filter element includes a support plate having permeate passages extending radially a short distance along the support plate, a separation medium mounted on the support plate, and a drainage layer disposed between the separation medium and the support plate. The drainage layer has a peripheral portion which overlaps the permeate passages.

In accordance with a yet further aspect of the invention, a filter element includes a substantially flat support plate having first and second sides and one or more radially extending permeate passages, a separation medium mounted on each side of the support plate, and a drainage layer disposed between each separation medium and the support plate, wherein the drainage layer communicates with the permeate passages in the support plate.

Filter elements embodying these aspects of the invention are very economical to manufacture and yet are highly reliable. For many embodiments, each membrane support plate can be a flat, smooth member of constant thickness with no surface irregularities formed in it, so it is inexpensive to manufacture. The absence of surface irregularities or thickness variations also permits the outer surfaces of the filter membrane to be made very smooth, resulting in improved filtering conditions. Since the membrane support plate has a very simple shape and does not require complicated forming processes, it can have a very small thickness and a correspondingly low weight.

In accordance with a further aspect of the invention, a filter element includes a composite that includes a support plate, a separation medium, and a drainage layer disposed between the support plate and separation medium. The composite is free of a bonding layer.

In accordance with a still further aspect of the invention, a membrane module or a vibratory separation system includes a plurality of stacked filter elements as described in any of the preceding aspects of the invention.

In accordance with a still further aspect of the invention, a method of forming a filter element includes forming a composite comprising a support plate having a plurality of through holes, a plurality of sealing members each disposed at one of the through

holes, at least one separation medium disposed on a side of the support plate, applying heat and pressure to the composite to soften the sealing members, and cooling the composite to solidify the sealing members and form fluid-tight seals between the separation medium and a surface of the support plate at each of the through holes.

In accordance with a still further aspect of the invention, a method of forming a filter element includes forming a composite comprising a support plate having a plurality of through holes, a separation medium disposed on a side of the support plate, wherein each of the through holes contains a curable liquid material, allowing the curable liquid material within each through hole to cure to form a fluid-tight seal between the separation medium and a surface of the support plate.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram representation of a vibratory separation system of the present invention.

Figure 2 is a top plan view of a vibratory separation assembly of a vibratory separation system of the present invention.

Figure 3 is an elevation view in partial cross-section of the vibratory separation assembly taken along section line 3-3 in Figure 2.

Figure 4 is an elevation view in partial cross-section of the vibratory separation assembly taken along section line 4-4 in Figure 2.

Figure 5 is a schematic vertical cross-sectional view of a portion of one embodiment of a membrane module of the present invention.

Figure 6 is a plan view of a support plate of one of the filter elements in the membrane module of Figure 5.

Figure 7 is a schematic vertical cross-sectional view of a portion of the membrane module of Figure 5 showing drainage slots formed near the radial centers of the separation medium support plates.

Figure 8 is a plan view of a drainage layer for use with the support plate of Figure 6.

Figures 9-11 are schematic vertical cross-sectional views showing a portion of one of the filter elements of the membrane module of Figure 5 at various stages of its assembly, the filter element including a solid sealing member.

Figure 12 is a schematic vertical cross-sectional view of a portion of another

embodiment of a membrane module according to the present invention.

Figure 13 is a schematic vertical cross-sectional view of a portion of a further embodiment of a membrane module according to the present invention.

Figure 14 is a schematic vertical cross-sectional view of a portion of additional embodiments of a membrane module according to the present invention.

Figures 15-16 are schematic vertical cross-sectional views showing a portion of one of the filter elements of the membrane module of Figure 13 at various stages of its assembly, the filter element including a liquid sealing member.

DESCRIPTION OF PREFERRED EMBODIMENTS

As illustrated in Figure 1, an exemplary embodiment of the vibratory separation system of the present invention may include a vibratory separation assembly 100, a process fluid feed arrangement 300, a retentate recovery arrangement 400, and a permeate recovery arrangement 500. The vibratory separation assembly 100 generally comprises a drive mechanism 102 and a membrane module 104 having at least one process fluid inlet 106, a retentate outlet 108, a permeate outlet 110, and a permeate drain 114. The membrane module 104 also includes one or more filter elements, not illustrated in Figure 1. The membrane module 104 may also include a process fluid outlet 112 and a retentate inlet 113. The process fluid outlet 112 and retentate inlet 113 may be used by the process and retentate recirculation loops described in International Publication No. WO 97/02087, which has been incorporated by reference.

The process fluid feed arrangement 300 is connected to the process fluid inlets 106 of the vibratory separation assembly 100 and may include a tank, vat, reservoir, or other container 302 of process fluid, which is coupled to the process fluid inlets 106 via a feed line 304. The process fluid feed arrangement 300 may also include a pump assembly 306, which can comprise a positive displacement pump, in the feed line 304 for transporting the process fluid from the container 302 to the vibratory separation assembly 100. A pressure sensor 308 and a temperature sensor 310 coupled to the feed line 304 may also be included in the process fluid feed arrangement 300. Alternatively, the process fluid may be supplied from any suitable pressurized source and the process fluid feed arrangement 300 may include, in addition to or instead of the pump assembly 306, one or more control valves and/or flow meters for controlling the flow of process fluid through

the feed line 304 to the process fluid inlets 106 of the vibratory separation assembly 100.

The retentate recovery arrangement 400 is coupled to the retentate outlet 108 of the vibratory separation assembly 100. Where the vibratory separation system is a recirculating system designed to repeatedly pass the process fluid across the filter elements of the membrane module 104, the retentate recovery arrangement 400 may include a retentate return line 402 which extends from the retentate outlet 108 to the process fluid container 302. Where the vibratory separation system is designed to pass the process fluid only once across the filter elements of the membrane module 104, one or more valves 404 may be coupled to the retentate return line 402 to direct the retentate to a separate retentate container or reservoir 414, or away from the vibratory separation system. The retentate recovery arrangement 400 may also include a pump assembly 406, which can include a positive displacement pump, for transporting the retentate from the vibratory separation assembly 100 to the process fluid container 302. Alternatively, the retentate recovery arrangement 400 may include, in addition to or instead of the pump assembly 406, one or more control valves and flow meters coupled to the retentate return line 402 for transporting the retentate fluid from the vibratory separation assembly 100 to the process fluid container 302. A pressure sensor 408 and a temperature sensor 410 coupled to the retentate return line 402 may also be included in the retentate recovery arrangement 400. A valve 412 coupled to the retentate return line 402 may also be included in the retentate recovery arrangement 400 to control the flow rate of retentate exiting the membrane module 104.

The permeate recovery arrangement 500 is coupled to the permeate outlet 110 of the vibratory separation assembly 100 and may include a permeate recovery line 502 which extends from the permeate outlet 110 to a permeate container 504. One or more valves 506 may be coupled to the permeate recovery line 502 to direct the permeate away from the vibratory separation system. Further, pressure sensors 508, 510 and a temperature sensor 512 coupled to the permeate recovery line 502 may also be included in the permeate recovery arrangement 500. Alternatively, the permeate recovery arrangement 500 may include a pump assembly coupled to the permeate recovery line 502 for withdrawing permeate from the vibratory separation assembly 100.

The vibratory separation assembly 100, as stated above, preferably comprises generally two components: the membrane module 104 and the drive mechanism 102. The

membrane module 104 may be connected to a torsion spring 116 of the drive mechanism 102 or any suitable means for the transmission of vibratory forces as described in International Publication No. WO 97/02087. The drive mechanism 102 transfers vibratory forces, for example, in the form of orbital, oscillational, torsional, or linear vibratory motion, to the membrane module 104 to induce motion between the process fluid and the surface of each filter element. Preferably, the direction of vibration is in a plane perpendicular to the axis of the membrane module 104. The drive mechanism 102 may vibrate the membrane module 104 at a frequency in the range of about 5 to about 500 Hz, preferably about 10 to about 120 Hz, and more preferably in the range of about 20 to about 80 Hz, and even more preferably in the range from about 30 to about 70 Hz. For any size membrane, the amplitude of vibration may preferably be less than about 90 degrees and more preferably less than about 75 degrees. The amplitude of vibration, for example in a system utilizing a module having a diameter of 610 mm, may range from about 6.3 mm (approximately 1.2 degrees) to about 305 mm (approximately 57.3 degrees) or more as measured at the outer periphery thereof, more preferably from about 38 mm (approximately 7.2 degrees) to about 76.5 mm (approximately 14.3 degrees) inches, and even more preferably about 51 mm (approximately 9.5 degrees), as measured at the outer periphery thereof.

The membrane module 104 may comprise various geometries, e.g., a parallelepiped configuration, but is preferably constructed utilizing a substantially cylindrical configuration as illustrated in Figures 2-4. The membrane module 104 comprises a base plate assembly 118, a head plate assembly 120, and a plurality of filter elements 122 positioned and secured between the base plate assembly 118 and the head plate assembly 120. The membrane module 104 may have only one filter element 122 sandwiched between the head plate assembly 120 and the base plate assembly 118 but more preferably comprises a plurality of filter elements 122. For example, two, five, ten, twenty-five, fifty, seventy-five, one hundred, or more filter elements 122 may be secured between the head and base plate assemblies 120 and 118. The process fluid inlets 106 and the permeate drain 114 may be mounted to the base plate assembly 118. The retentate outlet 108 and the permeate outlet 110 may be mounted to the head plate assembly 120. The number of filter elements 122 comprising the membrane module 104 varies depending upon the particular application for which the vibratory separation assembly 100

is to be used.

The base plate assembly 118 may be constructed as a one piece, unitary structure, or may preferably be constructed from individual components as described in International Publication No. WO 97/02087. As shown in Figures 3 and 4, the base plate assembly 118 may comprise an upper process fluid channel 130 and a lower process fluid channel 132. Process fluid conduits 200 in the filter elements 122 communicate with the upper process fluid channel 130, and the process fluid inlets 106 communicate with the lower process fluid channel 132 as is illustrated in Figures 3 and 4. The base plate 124 may also comprise a permeate drain conduit 208 which connects a permeate conduit 202 in the filter elements 122 to a permeate drain 114.

The base plate assembly 118 may include a plurality of holes 140, 142, which are preferably circularly arranged around the outer periphery and an inner portion of the base plate assembly 118. These holes 140 are utilized to position bolts or other securing means which are used to position and secure the filter elements 122 between the head plate assembly 120 and the base plate assembly 118. The base plate assembly 118 may also include a plurality of holes 170, two of which are illustrated in Figures 3 and 4, circularly arranged around a lower portion of the base plate assembly 118. The torsion spring 116 may be connected to the base plate assembly 118 by a plurality of bolts 172 or other securing means, positioned through openings in an upper portion of the torsion spring 116 and through the plurality of holes 170 in the base plate assembly 118.

The head plate assembly 120 may be constructed as a one-piece, unitary structure, or may preferably be constructed from individual components as described in International Publication No. WO 97/02087. As shown in Figures 3 and 4, the head plate assembly 120 may comprise a central opening 180 with which the permeate outlet 110 communicates, a retentate outlet channel 182 in a lower surface thereof with which the retentate outlet 108 communicates, and a process fluid outlet channel 184 in a lower surface thereof with which the process fluid outlets 112 communicate. The head plate assembly 120 may also include a plurality of holes 190 circularly arranged around its outer periphery and in a center region thereof. These holes 190, 192 are arranged such that they are in alignment with holes 140, 142 in the base plate 124 and are utilized to position the bolts or other securing means which secure the filter elements 122 between the head plate assembly 120 and the base plate assembly 118. The surfaces of the head

plate assembly 120 and the base plate assembly 118 which interface with the filter elements 122 may be flat or sloped as described in International Publication WO 97/02087.

Although the filter elements 122 may be configured in a wide variety of ways, each filter element 122 preferably comprises a support plate 218 and a separation medium 262. One example of a preferred filter element 122 is illustrated in Figures 5-7. The support plate 218 in the example preferably appears identical from the top and the bottom, so only the top plan view of the filter element 122 is shown in Figure 6. The separation plate 218 may comprise a substantially circular disc having a central opening 220, and three sets of circularly arranged holes 230, 234, and 236. As shown in Figures 3 and 4, the central opening 220 of each of the filter elements 122 and the outermost set of circularly arranged holes 234 in the filter elements 122 form guides 194 and 196 for the bolts or other fastening means which are utilized to secure the filter elements 122 between the head plate assembly 120 and the base plate assembly 118. In the illustrated embodiment, the outermost set 234 comprises sixteen holes; however, more or fewer holes may be utilized. The central guide 194 may be a single opening in which all of the bolts are positioned. The outer guides 196 may each contain a single bolt.

With the filter elements 122 secured in position between the base plate assembly 118 and the head plate assembly 120, the remaining two sets of circularly arranged holes 230 and 236 align to form conduits. The innermost set of circularly arranged holes 230 may form a plurality of retentate conduits 198, one of which is illustrated in Figure 4, which communicate with the retentate outlet 108 via the retentate outlet channel 182. The retentate conduits may also be arranged to communicate with one or more retentate inlets. In the illustrated embodiments, this innermost set of circularly arranged holes 230 comprises six holes; however, more or fewer holes may be utilized, for example, eight holes. The intermediate set of circularly arranged holes 236 may form a plurality of process fluid conduits 200 which communicate with the process fluid inlets 106 via the pair of process fluid channels 130 and 132 and with the process fluid outlets 112 via the process fluid outlet channel 184. The intermediate set of circularly arranged holes 236 preferably comprises twelve holes; however, as before, more or fewer may be utilized. In addition, the central openings 220 in each of the filter elements 122 also form a conduit, specifically, a permeate conduit 202. A plurality of radially extending permeate drainage

slots 225 are formed in the support plate 218 between the central opening 220 and the vicinity of the retentate holes 230. The permeate conduit 202 communicates at one end with the permeate outlet 110 via the central opening 180 and at a second end with the permeate drain 114.

The membrane module 104 may also include inner and outer seals or spaces 240 and 242 mounted between the filter elements 122, as shown in Figures 5 and 7. The seals 240 and 242 may comprise any suitable material, such as a metallic, polymeric or elastomeric material. In one embodiment, the seals may comprise annular polymeric rings. The seals 240 and 242 preferably have a thickness greater than the thickness of the separation medium 262 and serve as a spacer such that a gap 268 is created between adjacent filter elements 122 in the membrane module 104. This gap 268, which is best illustrated in Figure 5, provides a process fluid flow channel or chamber along the upstream sides of adjacent separation media 262. Alternatively, the inner and outer peripheries of one or both sides of the support plate may be raised and thereby function similarly to the seals 240 and 242.

The inner seal 240 preferably has an inner diameter substantially equal to the diameter of the central opening 220 and an outer diameter less than the diameter on which the retentate holes 230 lie. The outer seal 242 preferably has an outer diameter substantially equal to that of the outer diameter of the support plate 218 and an inner diameter greater than the diameter on which the process fluid holes 236 lie. In addition, the outer seal 242 comprises a plurality of holes 244 which correspond to the outermost set of holes 234 in the support plate 218 as shown in Figure 6. The outer seal 242, as well as the inner seal 240, may comprise extra holes. These extra holes may be utilized to reduce the overall weight of the system by reducing the weight of the seal itself.

Various methods and materials may be used to bond the surfaces of the inner and outer seals 240 and 242 to the filter elements 122. For example, these surfaces may be welded, brazed, epoxied, or adhered, as disclosed in International Publication No. WO 97/02087. Further, a gasket (or sealant) may be placed between the filter elements and the inner and outer seals or between the filter elements at the inner and outer seals. For example, a flat, annular gasket may be positioned adjacent to the radially inner surface of each outer seal 240 and the radially outer surface of each inner seal 242, and these gaskets are compressed against adjacent filter elements including the separation media, by

tightening the bolts of the membrane module.

The laminar construction of the membrane module 104, where any desired number of filter elements 122 and inner and outer seals 240 and 242 are simply stacked and sealed to one another, provides a flexibility to the fabrication process which accommodates a wide variety of process conditions. The laminar construction also simplifies the structure of the membrane module. The laminated outer periphery of the membrane module preferably forms an outer containment wall which isolates the process fluid, the permeate, or both on the inside of the wall from the ambient environment on the outside of the wall. In addition, the laminated stack structure defines an inner laminated wall. In the exemplary embodiment, the outer laminated containment wall comprises a stack of filter elements 122 and outer seals 242, but in alternative embodiments it may be differently configured, e.g., as a stack of filter elements without any seals. By isolating the process fluid and the permeate from the ambient environment, the laminated containment wall obviates an outer membrane module housing. Not only does this simplify construction, but it also reduces weight, and, therefore, the moment of inertia.

Figure 5 is a vertical cross-sectional view of a portion of a membrane module 104 of an embodiment of a vibratory separation system according to the present invention. This embodiment includes a membrane module 104 having a plurality of filter elements 122 stacked atop each other with annular seals 240, 242 disposed between and fluidly sealed against adjacent filter elements 122. Gaskets 250, 252 are also preferably included adjacent to the seals 240, 242 as previously described. In this embodiment, each filter element 122 preferably comprises a support plate 218 and a separation medium 262 mounted on one or preferably each surface of the support plate 218. A drainage layer 219 for permeate which has passed through the separation medium 262 is preferably provided between each separation medium 262 and the surface of the support plate 218 on which the separation medium 262 is mounted. Thus, in this embodiment, permeate flows in the radial direction of each support plate 218 along the outer surfaces of the support plate 218 through the drainage layers 219.

The illustrated support plate 218 includes an outer region beyond the process fluid holes 236, an intermediate region between the process fluid holes 236 and the retentate holes 230, and an inner region within the retentate holes 230. The support plate 218 is preferably of constant thickness over its entire diameter and is preferably completely flat

without any height variations on either surface such as grooves, depressions, or projections (neglecting microscopic variations in height which are incidentally formed during the process of manufacture) over the entire intermediate region between the process fluid holes 236 and the retentate holes 230. Although it is possible for the support plate 218 to have variations in its thickness or in the height of its surfaces, such as grooves, depressions, projections, or other permeate passages in this region, such variations are less preferred for the operation of this embodiment since radial or lateral drainage of permeate can take place through the drainage layers 219. Preferably the surface of the support plate 218 is as smooth and flat as possible, at least in the intermediate region between the process fluid holes 236 and the retentate holes 230, so that the separation medium 262 disposed atop this region will be smooth and flat. A support plate 218 having a constant thickness over its entire diameter, as in the present embodiment, may be advantageous because it makes the support plate 218 more economical to manufacture and makes it possible for the support plate 218 to be very thin. For example, the support plate may have a thickness in the range from about 2.5 mm to about 0.05 mm and is preferably about 0.5 mm thick or less and more preferably about 0.25 mm thick or less. The diameter of the support plate 218 may vary with the particular application for which it is to be utilized. For example, the diameter may be in the range from about 50 mm to about 1300 mm, and preferably from about 250 mm to about 775 mm, and more preferably from about 500 mm to about 635 mm.

The support plate 218 may be constructed from any material having sufficient structural integrity, such as a suitable polymeric material, but is most preferably formed from a metallic material, such as stainless steel. Other metals which may be utilized are aluminum, brass, copper, titanium and bronze. The particular material utilized is preferably strong enough to withstand the vibratory forces generated by the drive mechanism 102 and is compatible with the particular process fluid being filtered.

When the filter elements 122 are assembled to form the membrane module 104, the seals 240 disposed near the radial centers of the support plates 218 and the gaskets mounted at the seals 240 are typically pressed into sealing contact with the separation media 262. The pressure applied to the separation media 262 by the seals 240 and the gaskets may substantially prevent permeate from flowing between the gaskets and seals 240 and the support plates 218. Permeate drainage passages, such as permeate drainage

slots 225, are preferably formed near the center of each support plate 218 to enable permeate to flow underneath the seals 240 and gaskets 250 and into the central opening 220, as shown in Figures 6 and 7. The permeate drainage slots 225 need not extend through the entire thickness of the support plate 218, but when the support plate 218 is thin, it is simpler to form the permeate drainage slots 225 by cutting through the entire thickness of the support plate 218. The number and size of the drainage slots 225 can be selected in accordance with the rate at which the permeate needs to pass into the central retentate passage.

As shown in Figures 7 and 8, each drainage layer 219 preferably overlaps the radially outer ends of the drainage slots 225 so that permeate can readily drain from the drainage layers 219 into the permeate drainage slots 225. The permeate drainage slots 225 may extend radially outwards from the center of the support plate 218 as far as desired. Preferably, they extend radially only a short distance along the support plate 218. In the illustrated embodiment, they extend only in the inner region of the support plate 218, such as to the vicinity of the retentate holes 230. For simplicity of manufacture, the drainage slots 225 extend along straight lines in this embodiment, but they may be curved, zigzag, or of other desired shape. If desired, the drainage slots 225 may be replaced by other structures providing drainage to the central openings 220 of the support plates 218, such as holes extending laterally through each support plate 218 extending between its central opening 220 and its upper and lower surfaces. If the flow direction of the permeate is reversed from that in the illustrated embodiment so as to be in the radially outwards direction of the support plates rather than in the radially inwards direction, permeate drainage passages can be formed in the outer peripheral region of the support plate instead of along its inner peripheral region.

The separation medium 262 may comprise any suitable medium useful for microfiltration, ultrafiltration, nanofiltration, or reverse osmosis, such as a porous or semipermeable polymeric film or membrane or a woven or non-woven sheet of polymeric or non-polymeric fibers or filaments. Alternatively, the separation medium 262 may comprise a porous metal media, such as the media available from Pall Corporation under the trade designations PMM and PMF, a fiberglass media, or a porous ceramic media. For the exemplary embodiment the separation medium preferably comprises a supported or unsupported polymeric membrane. The membrane preferably comprises a polymeric

material such as polyamide, polyvinylidene fluoride, polytetrafluoroethylene, polysulfone, polyethersulfone, polyethylene, and polypropylene. More preferred membranes are polyamide, e.g., nylon, and polytetrafluoroethylene membranes. Further, the separation medium 262 may comprise one or more layers.

Each separation medium 262 may extend over as much of the area of the corresponding support plate 218 as desired. The separation medium 262 may also include an outer portion extending outwardly from the drainage layer 219, an inner portion extending inwardly from the drainage layer 219, and an intermediate portion coextensive with the drainage layer 219. In order to make maximum use of the surface area of the support plates 218, a separation medium 262 is preferably mounted on both sides of each support plate 218 in the present embodiment, but alternatively, a separation medium 262 may be mounted on a single side of the support plate 218. When separation media 262 are mounted on both sides of a support plate 218, the separation media 262 need not be of the same material and need not have the same surface area, thickness, or other dimensions. In some embodiments of the filter element, the outer periphery of the separation medium 262 may preferably terminate just short of the inner surface of the outer seal 242, as shown in Figure 5. The distance 263 between the outer periphery of a separation medium and the inner surface of the outer seal 242 may vary. In some embodiments, for example, the distance 263 may range from about 3 mm to about 6.5 mm.

The drainage layers 219 can be made of any materials having good edgewise flow characteristics e.g., (low resistance to flow in the direction parallel to the surface of a support plate 218) to enable permeate which has passed through the separation media 262 to readily flow to the permeate drainage slots 225 at the center of the support plate 218. Woven or non-woven fabrics, woven or non-woven meshes, or other materials conventionally used as drainage materials in filters can be employed as the drainage layers 219. Non-woven fabrics are particularly suitable as the drainage layers 219 because they are smoother than meshes, for example, and result in the separation medium 262 having a flatter, more regular surface than when other drainage materials, such as meshes, are employed. The thickness and porosity of the drainage layers 219 can be selected in accordance with the viscosity and desired flow rate of the permeate so as to restrict the pressure drop of permeate flowing through the drainage layers 219 to a desired level. In a

preferred embodiment, the thickness of the drainage layer is preferably less than 0.6 mm.

Figure 8 is a plan view of the drainage layer 219 employed in the present embodiment, with the outline of the support plate 218 on which it is mounted shown in dashed lines. The illustrated drainage layer 219 comprises a non-woven polyester fabric available in a wide range of grades from Reemay, Inc. of Old Hickory, Tennessee under the trade designation REEMAY. It has a generally circular outer periphery and a generally circular hole 235 at its center surrounding the central opening 220 in the support plate 218. In order to make it easier to seal the separation medium 262 to the support plate 218 in the vicinity of the process fluid holes 236 and retentate holes 230 the drainage layer 219 may be formed with cutouts 237 surrounding the holes 236, 230 so that in the immediate vicinity of the holes 236, 230, the drainage layer 219 will not be present between the separation medium 262 and the support plate 218.

Each separation medium 262 is preferably attached to the adjoining drainage layer 219 and/or to the opposing surface of the support plate 218 to prevent shearing forces from peeling the separation medium 262 off the drainage layer 219 or the support plate 218 during operation of the separation system. The separation medium 262 may be attached to the drainage layer 219 or the support plate 218 in any suitable manner. For example, the separation medium 262 may be welded or bonded by an adhesive or a solvent to the drainage layer 219 or the support plate 218. The drainage layer 219 may also be attached to the support plate in any suitable manner which allows permeate to drain to the permeate drainage slots. The surface of the support plate 218 may be roughened, for example, by oxidation, prior to attaching the separation medium 262 or the drainage layer 219 to the support plate 218. This roughening of the surface typically aids the bonding process. The attachment of the separation medium and/or the drainage layer may be continuous or discontinuous and in various locations or regions.

In the present embodiment, attachment preferably is performed using a heat-bondable bonding layer, such as a bonding layer 241 formed of a non-woven web of multicomponent thermoplastic fibers of the type described in detail in U.S. Patent Application No. 08/388,310 and UK Publication No. 2,297,945, which are incorporated herein by reference. However, the bonding layer may be of suitable type. For example, the bonding layer may be an adhesive bonded layer or a solvent bonded layer.

The multicomponent thermoplastic bonding layer 241 may comprise fibers of at

least a first polymer and a second polymer such that the second polymer is present on at least a portion of the surface of the multicomponent fibers and has a melting temperature below the melting temperatures of the first polymer. For example, the multicomponent fibers may comprise at least about 60 weight percent of the first polymer and no more than about 40 weight percent of the second polymer.

The multicomponent fibers of the nonwoven web can be prepared from any suitable polymers. Preferably, the multicomponent fibers of the nonwoven web will be prepared from suitable polyolefins. Suitable polyolefins include polyethylene, polypropylene, and polymethylpentene. The first polymer is preferably polypropylene, with the second polymer preferably being polyethylene. The fibers of the nonwoven web can be prepared by any suitable means and formed into a nonwoven web by any suitable means, such as the conventional Fourdrinier paper making processes. While the multicomponent fibers are preferably bicomponent fibers, i.e., fibers prepared from only two polymers, the multicomponent fibers can be prepared from more than two polymers, i.e., the first and/or second polymers as described herein can be thought of as polymer blends.

The particular combination of polymers for the multicomponent fibers may be chosen such that the melting temperatures of the first and second polymers differ sufficiently enough that melting or softening of the second polymer can be effected without adversely affecting the first polymer. Thus, the first polymer preferably has a melting temperature at least about 20°C higher, more preferably at least about 50°C higher, than the melting temperature of the second polymer. The second polymer will typically have a melting temperature of about 110°C to about 200°C, more typically about 110°C to about 150°C. Specific examples of suitable multicomponent fibers for use in the web include Celbond T105 and T106 fibers (Hoechst-Celanese, Salisbury, North Carolina) which comprise 100% bicomponent, concentrically oriented fibers having a linear low density polyethylene sheath with a melting temperature of 127°C and a polyester core with a melting temperature of 256°C.

Each bonding layer 241 preferably extends over substantially the same area as the adjoining separation medium 262 so that in those regions where the drainage layer 219 is present between the separation medium 262 and the support plate 218, the bonding layer 241 attaches the separation medium 262 to the drainage layer 219, while in those regions

where the drainage layer 219 is not present (such as within the cutouts 237 of the drainage layer 219), the bonding layer 241 attaches the separation medium 262 directly to the support plate 218. In the present embodiment, each bonding layer 241 is used primarily for the purpose of attaching the separation medium 262 to an adjoining member and, secondarily, for reinforcing the separation medium 262 to increase its peel strength, so the bonding layer 241 is preferably as thin as possible. Alternatively, the bonding layer 241 can have a thickness so as to provide drainage for fluid in the space between the separation medium 262 and the support plate 218. For example, the bonding layer 241 can be made to function as a drainage layer in addition to or instead of the drainage layer 219 employed in the present embodiment.

The attachment of the separation medium 262 to the drainage layer 219 and the support plate 218 is preferably effected by subjecting the bonding layer to a temperature above the softening temperature, and possibly above the melting temperature, of the second polymer but below the softening and melting temperatures of the first polymer, the separation medium 262, the drainage layer 219, and support plate 218. In other words, the bonding layer is subjected to a temperature sufficient to at least partially soften and possibly melt the second polymer without significantly softening or melting the other components of the filter element. This process is described in U.S. Patent Serial No. 08/388,310 and U.K. Patent Application GB 2,297,945A, assigned to the same assignee as the present invention.

Although each bonding layer 241 is capable of forming a strong connection between the adjoining separation medium 262 and the drainage layer 219 or the support plate 218, it may not form a fluid-tight seal between the separation medium 262 and the drainage layer 219 or the support plate 218. For example, the thermoplastic multicomponent bonding layer 241 is generally porous (i.e., it has interstices between its fibers through which fluid can flow) and has a finite thickness. Therefore, when the separation medium 262 extends to the vicinity of the process fluid holes 236 or retentate holes 230, a sealing mechanism is preferably provided to prevent leakage of fluid through the bonding layer 241 in either direction between the holes 236, 230 and the space between the separation medium 262 and the support plate 218.

In some embodiments, the sealing mechanism at the process fluid and retentate holes 236, 230 comprises sealing members 245 disposed at the holes 236, 230 which

soften or melt when heat and/or pressure are applied thereto to fill the interstices in the bonding layer 241 and form a fluid-tight seal in the vicinity of the process fluid holes 236 and the retentate holes 230. The sealing members 245 may have a variety of shapes and can be disposed in a variety of locations, as long as they can form a fluid-tight seal at the holes 236, 230. For example, the sealing members 245 may be inserts which are inserted into the holes 236 and 230, or they may comprise members such as discs, sheets, or plates which are placed atop the support plates 218 at opposite ends of the holes 236, 230 on opposite sides of the support plates 218 without being inserted into the holes.

For example, each of the sealing members 245 may comprise a solid cylindrical insert disposed in one of the holes 236, 230 and having a central hole 249 formed in it for the passage of fluid. The solid sealing members 245 may initially be hollow, or the holes 249 may be formed in the sealing members 245 during the assembly of the filter elements 122. Preferably, each sealing member 245 is preferably immobilized within the hole 236, 230 in which it is disposed so that it can resist external forces applied to it and provide good support for the separation media 262 on either side of the support plate 218, but it is also possible for the sealing members 245 to be loosely disposed in the holes 236, 230. The outer peripheral shape of the illustrated sealing members 245 is the same as the inner peripheral shapes of the holes 236 and 230 (e.g., circular), but the peripheral shapes need not be the same as each other. For example, the holes 236, 230 may be circular while the sealing members 245 have a polygonal periphery or vice versa. In the illustrated embodiment, in order to securely attach the sealing members 245 to the support plates 218, the holes 236, 230 which receive the sealing members 245 are made larger than the holes 249 to be cut through the sealing members 245 so that the portions of a sealing member 245 on the top and bottom surfaces of the support plate 218 will be structurally linked with each other through the thickness of the support plate 218.

Each sealing member 245 may be made to form a seal by heating at least a portion of the sealing member 245 to a temperature at which it softens or melts so as to become at least somewhat fluid, and then applying pressure to the sealing member 245 to force the softened or melted portion into the bonding layer 241 so as to fill the interstices between the fibers of the bonding layer 241 and thereby prevent fluid from flowing through the interstices. Generally, it is sufficient to soften the sealing member 245 without melting it, but it is possible to heat a portion of the sealing member 245 to its melting point if the

flow of the sealing member 245 in a molten state can be sufficiently controlled. As the sealing member 245 fills the interstices of the bonding layer 241, it may come into intimate contact with the separation medium 262 as well. Depending upon the material of which the separation medium 262 is made, the sealing member 245 may also enter into the pores of the separation medium 262. If the drainage layer 219 is present between the separation medium 262 and the support surface in the vicinity of the holes 236 and 230, the sealing member 245 may also flow into and fill the interstices of the drainage layer 219. However, it is generally preferable if the drainage layer 219 is cut away around the holes 236, 230 to minimize the space which must be filled by the sealing member 245. While heating alone may be sufficient to cause the sealing member 245 to fill the interstices within the bonding layer 241, it is generally preferable to also apply pressure to the softened or melted portions of the sealing member 245, since pressure can help to force the sealing member 245 into the bonding layer 241 more uniformly and to make the sealing member 245 as flat as possible at the completion of sealing so that the separation medium 262 disposed atop the sealing member 245 will be flat and smooth. Pressure can also be used to decrease the thickness of the sealing member 245, or to cause it to expand to fill the hole 236, 230 if it does not initially do so. Pressure can be applied in various ways, such as by using rollers, wheels, flat plates, or plungers. The member which applies the pressure can itself be heated, or the sealing member 245 can be heated by a different member.

The application of pressure will frequently force the sealing member 245 into sealing contact with the support plate 218 around the entire periphery of the hole 236, 230 at which the sealing member 245 is disposed, but sealing contact between the sealing member 245 and the support plate 218 may not be necessary. For example, in the present embodiment, since the sealing member 245 is sealed to the separation media 262 at both of its ends, fluid is prevented from flowing between the interior of the hole 249 and the spaces between each separation medium 262 and the support plate 218, so sealing contact between the sealing member 245 and the support plate 218 is optional.

If a portion of the sealing member 245 extends to or is disposed on the exterior of the hole 236, 230 at which the sealing member 245 is disposed, the application of pressure may cause the sealing member 245 to spread radially outwards from the edges of the hole over one or both of the top and bottom surfaces of the support plate 218. For example, in

one form of the present invention, the sealing member 245 may have an initial height prior to the application of pressure which is greater than the thickness of the support plate 218 at the hole 236 and 230 in which the sealing member 245 is inserted, such as approximately 0.05 mm or more greater than the thickness, with the material in the portions of the sealing member 245 extending outside the holes flowing radially outwards from the hole to form a seal between the separation medium 262 and the support plate 218 around the hole 236, 230. However, the initial height of the sealing member 245 may be the same as or less than the thickness of the support plate 218 at the hole 236, 230 in which it is inserted, with substantially none of the material forming the sealing member 245 flowing outside the hole 236, 230 during the application of heat and pressure to the sealing member 245. For example, instead of the softened portions of the sealing member 245 flowing out of the hole in which it is disposed, the softened portions may remain in the hole (in the form of a pool of softened material, for example) with the bonding layers 241 being forced against or into the softened material by the application of pressure.

The extent of the regions in which the sealing members 245 fill the interstices of the bonding layers 241 may vary. In the present embodiment, each sealing member 245 preferably fills the interstices of the bonding layers 241 which it contacts over substantially the entire area of each of the lengthwise end surfaces of the sealing member 245, but the regions may be smaller than the end surfaces. Preferably, the regions extend continuously around the entire periphery of each end of the hole 249.

The solid sealing members 245 can be made of any material which can soften or melt when heated so as to fill the interstices between the fibers of the bonding layer 241 and which, when it solidifies after softening or melting, is preferably without micropores. The softening or melting points of the sealing members 245 are not critical but are preferably above the service temperature of the filter element 122 and are preferably such that the heating required to soften or melt the sealing members 245 does not damage other portions of the filter element 122 subjected to the heating. Thermoplastic polymeric materials are frequently suitable for the sealing members 245. When the filter element 122 includes a bonding layer 241, it is convenient if the sealing members 245 are made of a material which softens or melts at or below the temperature to which the bonding layer 241 is heated to adhere it to the separation medium 262 or other member. As stated above, the second polymer in the bonding layer 241 will typically having a softening

temperature which is at least about 20°C lower and preferably at least about 50°C lower than the softening temperature of the first polymer in the bonding layer 241. If the sealing members 245 have a softening or melting point in the same temperature range as the softening temperature of the second polymer with respect to the softening temperature of the first polymer, i.e., at least about 20°C lower and preferably at least about 50°C lower than the softening temperature of the first polymer, the sealing member 245 can be softened or melted and the second polymer can simultaneously be softened without softening the first polymer in the bonding layer 241. For example, when the bonding layer 241 is formed of the above-described T105 or T106 fibers, which comprise polyester as the first polymer and polyethylene as the second polymer, it is convenient to form the sealing member 245 of polyethylene having a melting point in the range of 100°C to 160°C, for example, which falls within the temperature range typically used to adhere the bonding layer 241 to the separation medium 262 with a laminator. The softening or melting point of the sealing member 245 may be less than, greater than, or equal to the softening temperature of the second polymer in the bonding layer 241 while still being in the above-described temperature range below the softening temperature of the first polymer in the bonding layer.

It is also possible for the sealing members 245 to have a higher softening or melting point than the softening temperature of either of the components of the bonding layer 241, if the sealing members 245 can be softened or melted without softening the first polymer of the bonding layer 241, or if any softening of the first polymer is limited to the immediate vicinity of the sealing members 245.

While a thermoplastic polymeric material is frequently suitable for the solid sealing members 245, depending upon the materials of which other portions of the filter elements 122 are formed, it is may be possible to employ metals as the solid sealing member 245, particularly those with a relatively low melting point such as solders. The sealing members are not restricted to use with the particular filter elements shown in the drawings. For example, the sealing members be employed in a filter element not having drainage layers or bonding layers or in a filter element having additional layers.

The solid sealing members 245 can be softened or melted by any convenient method. If the sealing members 245 have a suitable softening or melting point, they may be softened or melted by the equipment used to soften the bonding layer 241, such as a

conventional hot plate or a laminator. Examples of other possible equipment are ultrasonic heating equipment, induction heaters, and heated rods which are pressed against the opposite ends of the sealing members 245.

An example of a method of forming the filter elements 122 of Figure 5 will be described while referring to Figures 9 - 11, which are schematic vertical cross-sectional views of a region of one of the filter elements 122 surrounding one of the process fluid holes 236 or retentate holes 230. These drawings are not to scale, and the relative dimensions of some of the layers have been exaggerated for clarity. A precut, circular separation medium 262 may be first placed atop a table or other flat surface. A bonding layer 241 comprising a precut, circular web of a two-component polymer having the same diameter as the separation medium 262 may be placed directly atop the separation medium 262. A precut drainage layer 219 like the one shown in Figure 8 may then be placed concentrically atop the bonding layer 241. Next, a support plate 218 like the one shown in Figure 6 may be placed concentrically atop the drainage layer 219 with the process fluid holes 236 and retentate holes 230 in the support plate 218 aligned with the cutouts 237 in the drainage layer 219. In one embodiment, the support plate 218 may be a flat, stainless steel disc with a uniform thickness of approximately 0.5 mm or less. A solid sealing member 245 in the form of a cylindrical insert without a central hole may be inserted into each of the process fluid holes 236 and retentate holes 230 in the support plate 218. Each sealing member 245 preferably fits snugly into the corresponding hole 236, 230 around its entire periphery and may have an initial height of approximately 0.762 mm prior to being heated so that it protrudes outwards from both ends of the holes. The sealing member 245 may be made of high density polyethylene having a softening temperature in the same range as the softening temperature of the low-melting component (i.e., the second polymer) of the bonding layer 241. In some embodiments, another drainage layer 219, another bonding layer 241, and another separation medium 262 identical to the corresponding layers disposed underneath the support plate 218 may then be placed concentrically atop the support plate 218, with the cutouts 237 in the upper drainage layer 219 aligned with the holes 236, 230 in the support plate 218. In this state, the stacked components appear as shown in Figure 10. Due to the cutouts 237 in the drainage layers 219 adjoining the holes 236 and 230, the two drainage layers 219 are not visible in this figure. Alternatively, the second set of drainage layer 219, bonding layer

218, and the separation medium 262 on the top of the support plate 218 may be different from the first set of components on the bottom of the support plate 218. Further, in some other embodiments the stacked components may only have either the first or second set of components. On other words, there may be a set of components on only one side of the support plate 218.

The stack of components of Figure 9 may then be fed into a conventional laminator having a suitable heating mechanism and nip rolls for applying pressure to the stack. As the stack of components passes through the laminator, the second polymer component of the bonding layer 241 is softened to adhere to the separation medium 262 and the drainage layer 219 or the support plate 218. At the same time, at least the portion of the sealing member 245 protruding out of the hole 236, 230 is softened and, under the pressure applied by the nip rolls of the laminator, is forced into the bonding layers 241 abutting its end surfaces to fill the interstices between the fibers of the bonding layers 241 in these regions. At the same time, a portion of the sealing member 245 may flow radially outwards from the hole for a certain distance, as shown by reference numeral 247. The portion which flows outwards may also be forced into and fill the interstices in the bonding layer 241. Upon emerging from the laminator, the stack of components is allowed to cool to room temperature, and the molten or softened portions of the bonding layer 241 and the sealing member 245 solidify, thereby adhering the separation medium 262 to the drainage layer 219 or the support plate 218 and forming a fluid-tight seal to the separation medium 262. Figure 10 schematically illustrates the filter element 122 at the completion of solidification of the bonding layer 241 and the sealing member 245.

Either before or after cooling takes place, a hole 249 is cut through the sealing member 245 and the two layers 262, 219 on its top and bottom surface to provide a passage for fluid extending through the entire thickness of the filter element 122. The hole 249 may be formed with a punch, a drill, or any other suitable mechanism. Alternatively, the sealing member may already contain the hole when the sealing member is inserted in the holes of the support plate. Then, only the permeably membrane and the bonding layer are punched or drilled. Figure 11 shows the filter element 122 after the formation of the hole 249. The hole 249 in the sealing member 245 may have any desired shape, and it may have any diameter suitable for the amount of fluid which needs to flow through it, up to the diameter of the hole 236, 230 in the support plate 218 in which the

sealing member 245 is inserted, with the diameter preferably being chosen so that the interstices of the bonding layer 241 are filled by the sealing member 245 around the entire circumference of the hole 249.

Another embodiment of a membrane module 104B including a plurality of alternative filter elements 122B is shown in Figure 12. The membrane module 104B shown in Figure 12 may be similar to the membrane module 104 shown in Figure 5 except that the filter element 122B includes an additional bonding layer 241B disposed between the drainage layer 219 and the support plate 218. The additional bonding layer 241B may extend only under the drainage layer 219 or it may be generally coextensive with the original bonding layer 241, as shown in Figure 12. Further, the additional bonding layer 241B may have cutouts in the vicinity of the permeate slots 215 so as not to hinder permeate flow from the drainage layer 219 to the permeate conduit 220. In embodiments where the additional drainage layer 241B is coextensive with the original drainage layer 241, each sealing member 245 is preferably arranged to fill the interstices in both bonding layers 241, 241B to form a fluid-tight seal in the vicinity of the process fluid or retentate holes 236, 230. By providing the additional bonding layer 241B, the drainage layer 219 is securely attached to the support plate 218 and is prevented from being lifted off the support plate 218 when the membrane module 104B is vibrated.

Another embodiment of a membrane module 104C including a plurality of alternative filter elements 122C is shown in Figure 13. The membrane module 104C shown in Figure 13 may be similar to the membrane module 104B shown in Figure 12 except that the filter element 122C does not include a bonding layer between the separation medium 262 and the drainage layer 219. Rather, the bonding layer 241C extends between the separation medium 262 and the support plate 218 and between the drainage layer 219 and the support plate 218, except in the vicinity of the permeate slots 215. By not providing a bonding layer between the separation medium 262 and the drainage layer 219, the filter element 122C may be slightly thinner and lighter than the filter element 122B shown in Figure 12. Further, the filter element 122C may have a lower resistance to permeate flow than the filter element 122, 122B of Figure 5 or 12.

Another embodiment of a membrane module 104D including a plurality of alternative filter elements 122D is shown in Figure 14. The membrane module 104D shown in Figure 14 may be similar to the membrane module 104C shown in Figure 13

except that the filter element 104D includes no bonding layer, either between the support plate 218 and the separation medium 262 or the drainage layer 219 or between the separation medium 262 and the drainage layer 219. Instead, the separation media 262, and hence the drainage layers 219, are secured to the support plates 218 by the gaskets 250, 252 and/or the seals 240, 242. For example, as shown in Figure 14, the outer gaskets 252, the inner gaskets 250, and the inner seals 240 are pressed against the outer and inner peripheries of the separation media 262 by the bolts in the membrane module 104D. In addition, the separation media 262 may be secured in place on the support plates 218 by the sealing members 245 in the process fluid and retentate holes 236, 230. By eliminating the bonding layers, the filter elements 122D may be thinner and lighter than any of the previous filter elements and the resistance to permeate flow may be very low.

In each of the previous embodiments, solid sealing members 245 have been used to seal the process fluid and retentate holes 236, 230 of the filter elements. The solid sealing members 245 and the preferred multi-fiber bonding layers have been especially useful together because both are heat-activated, e.g., both the sealing members and the bonding layers may be activated during a single lamination process involving the application of heat and pressure. However, many separation media, including many ultrafiltration, nanofiltration, and reverse osmosis polymeric membranes, may be damaged when heated.

Accordingly, another embodiment of a membrane module 104E including a plurality of alternative filter elements 122E is also shown in Figure 14. The membrane modules 104D, 104E and the filter elements 122D, 122E may be similar except that the sealing member 245E is a material that may be initially applied as a liquid and allowed to harden or cure to form the sealing member 245B. A wide variety of curable materials are available including many thermosetting materials, such as epoxy and silicone, which cure at low temperatures, e.g., room temperature, or upon radiation, e.g., UV radiation. A preferred material is a thermosetting polyurethane. Sealing members formed from a curable material do not require the application of heat to harden and, therefore, damage to heat sensitive media may be avoided.

An example of a method of forming the filter elements 122E of Figure 14 will be described while referring to Figures 15 and 16. These drawings are not to scale and the relative dimensions of some of the layers have been exaggerated for clarity. A precut

circular separation medium 262 may be first placed atop a table or other flat surface. A precut drainage layer like the one shown in Figure 8 may be placed concentrically atop the separation medium 262. Next, a support plate 218 like the one shown in Figure 6 may be placed concentrically atop the drainage layer 219 with the process fluid holes 236 and the retentate holes 230 in the support plate aligned with the cutouts 237 in the drainage layer 219. Again, the support plate 218 may preferably be a flat stainless steel disc with a uniform thickness of about 0.5 mm or less. A curable liquid material is then deposited in each of the process fluid and retentate holes 236, 230. The curable liquid may slightly underfill, substantially fill, or, preferably, overfill each hole 236, 230. Another drainage layer 219 and another separation medium 262 identical to the corresponding layers underneath the support plate 218 may then be placed concentrically atop the support plate 218, with the cutouts 237 in the drainage layer 219 aligned with the holes 236, 230 in the support plate 218. In this state, the stacked components appear as shown in Figure 15. Due to the cutouts in the drainage layers, the two drainage layers are not visible in Figure 15. In some embodiments, the curable liquid may be applied, in selected spots, strips, regions, between the separation media and the support plates, between the separation media and the drainage layers, and/or between the drainage layers and the support plates to help adhere the components to one another.

The stack of components may then be pressed, for example, between a pair of plates. As the stock is compressed, the liquid material contacts, and may at least slightly penetrate, the separation media 262. At the same time, if the holes 236, 230 are overfilled, the liquid material may be forced radially beyond the edges of the holes, forming a lip over the edges of the holes. The stack of components is preferably maintained under pressure until the liquid material hardens. While the stack may be maintained under pressure, there is preferably no application of heat, the liquid material preferably being a material which cures without the application of heat, e.g.,, at room temperature. After the liquid material cures, a hole 249 is cut through the hardened material and the two separation media 262, providing a hollow cylindrical sealing member 245B sealed to the separation media 262. The hole 249 may be formed with a punch, a drill, or any other suitable mechanism for providing a fluid passage extending through the entire thickness of the filter element 122E.

Once the filter elements 122-122E have been assembled, they may be combined

with the inner and outer seals 240, 242 and gaskets 250, 252 to form a membrane module 104-104E, which can be employed in a vibratory separation system. Any of the embodiments shown in Figures 5 and 12-14 may be used to describe the modes of operation of a vibratory separation system.

For example, in a preferred mode of operation of a vibratory separation system incorporating the membrane module of Figure 5 process fluid is directed under pressure into the membrane module 104 through the process fluid inlets 106 which are illustrated in Figures 3 and 4 by a pump, as illustrated in Figure 1, or by any other means suitable for delivery of the process fluid. The process fluid flows through the process fluid inlets 106, into the process fluid conduits 200 via the process fluid channels 130, 132, and through the process fluid chambers 260 to the retentate conduits 198. As the process fluid flows past the separation media 262 in the process fluid chambers 260, the membrane module 104 is vibrated by the drive mechanism 102 to create a shear flow boundary layer at the surfaces of the separation media 262 facing the process fluid, i.e., the upstream surfaces on the top and bottom of each filter element. Preferably, there are no significant protrusions which would inhibit fluid flow across the surfaces of the separator media 262. Accordingly, as the membrane module 104 is vibrated by the drive mechanism 102, the bulk of the process fluid between the separation media 262 of adjacent filter elements 122 does not move with the separation media 262. Therefore, there is relative vibratory movement between the process fluid and the separation media, and it is this relative movement that generates dynamic flow conditions which tend to prevent the deposition of foulants, such as particulate matter or colloidal matter, in the vicinity of the separation media 262. Therefore, fouling of the separation media 262 is greatly reduced.

As the membrane module 104 vibrates, a portion of the process fluid, i.e., the permeate, passes through the separation media 262 into the sealed space between the separation media 262 and the support plate 218. The permeate then flows edgewise through the drainage layer 219 towards the permeate conduit 202; in other words, the permeate flows laterally through the drainage layer 219 in parallel with the separation medium 262 and the support plate 218 in a radial direction towards the center of the support plate 218. Next, the permeate exits the drainage layer 219, enters the drainage slots 225, and then enters the permeate conduit 202. The permeate is directed to the permeate outlet 110 in the head plate assembly 120 where it may be recovered for various

purposes through the permeate recovery arrangement 500, as illustrated in Figure 1.

The portion of the process fluid which does not pass through the separation media 262, i.e., the retentate, flows through the process fluid chambers 260 into the retentate conduits 198. The retentate flows through the retentate conduits 198, into the retentate outlet channel 182 in the head plate 196 and out through the retentate outlet 108 in the head plate assembly 120 where it flows into the retentate recovery arrangement 400.

Although the inventions have been shown and described in several embodiments, it is apparent that departures from these embodiments may suggest themselves to those skilled in the art and may be used without departing from the spirit and scope of the inventions. For example, the invention includes one or more features of any of the embodiments combined with one or more features of the other embodiments. As an example, the sealing member formed from a curable liquid material may be incorporated into a filter element having a bonding layer such as a heat activated bonding layer. As another example, different alternative filter elements may be combined in the same membrane module. Further, one or more features of any of the embodiments may be eliminated without departing from the invention. As one example, the sealing members 245, 245B may be eliminated from any of the embodiments and, for example, may be replaced with metal islets. As another example, the drainage layer may be eliminated from any of the embodiments and, for example, may be replaced by passages in the support plate. As yet another example, a filter element may include a bonding layer bonding only the inner region (or outer region) of the separation medium to the support plate while the outer region (or inner region) is mechanically pressed against the support plate. In addition, one or more of the features of any of the embodiments may be modified without departing from the invention. As one example, the cutouts on the drainage layer may be eliminated and the sealing members may seal the drainage layer as well. As another example, a filter element may include only two bonding layers, one between the outer portion of the separation medium and the support plate and another between the inner portion of the separation medium and the support plate. The present invention is thus not restricted to the particular embodiments described and illustrated, but should be constructed to include all modifications that may fall within the scope of the appended claims.

What is claimed is:

1. A filter element mountable in a vibratory separation system, the filter element comprising:

a support plate having at least one through hole;

a separation medium mounted on the support plate;

a sealing member disposed at the hole to prevent fluid from flowing from the hole between the support plate and the separation medium.

2. The filter element of claim 1 further comprising at least one bonding layer disposed between the support plate and the separation medium at the hole, wherein the sealing member prevents fluid from flowing through the bonding layer at the hole.

3. The filter element of claim 2, wherein the bonding layer has interstices, and the sealing member fills the interstices of the bonding layer to prevent fluid from flowing through the bonding layer at the hole.

4. The filter element of any one of the preceding claims, wherein the sealing member is disposed in the hole.

5. The filter element of any one of the preceding claims, wherein the sealing member extends radially outwards from the hole.

6. The filter element of any one of the preceding claims, wherein the sealing member extends over an entire length of the hole.

7. The filter element of any one of the preceding claims, wherein the support plate comprises a metal.

8. The filter element of any one of the preceding claims, wherein the sealing member comprises a polymeric material.

9. The filter element of any one of the preceding claims, wherein the sealing member comprises a curable material.

10. The filter element of claim 9, wherein the sealing member comprises a temperature curable material.

11. The filter element of claim 9, wherein the sealing member comprises a time curable material.

12. The filter element of claim 9, wherein the sealing member comprises a radiation curable material.

13. A filter element mountable in a vibratory separation system, the filter element comprising:

a support plate;

a separation medium mounted on the support plate; and

a drainage layer disposed between the separation medium and the support plate, the drainage layer having a thickness less than 0.6 mm.

14. A filter element mountable in a vibratory separation system, the filter element comprising:

a support plate having permeate passages extending radially a short distance along the support plate;

a separation medium mounted on the support plate; and

a drainage layer disposed between the separation medium and the support plate, the drainage layer having a peripheral portion which overlaps the permeate passages.

15. A filter element mountable in a vibratory separation system, the filter element comprising:

a support plate;

a separation medium mounted on the support plate;

a drainage layer disposed between the separation medium and the support plate; and

a bonding layer disposed between the separation medium and the drainage layer.

16. A filter element mountable in a vibratory separation system, the filter element comprising:

a support plate;

a separation medium mounted on the support plate;

a drainage layer disposed between the separation medium and the support plate; and

a bonding layer disposed between the support plate and the drainage layer.

17. The filter element of claim 16, wherein the bonding layer is a first bonding layer, the filter element further including a second bonding layer disposed between the separation medium and the drainage layer.

18. A filter element mountable in a vibratory separation system, the filter element comprising:

a support plate;

a separation medium mounted on the support plate and having an inner portion, an intermediate portion and an outer portion;

a drainage layer disposed between the separation medium and the support plate in the intermediate portion of the separation medium; and

a bonding layer disposed between the separation medium and the support plate in the inner portion of the separation medium to bond the separation medium to the support plate.

19. The filter element of claim 18, wherein the bonding layer is a first bonding layer, the filter element further including a second bonding layer disposed between the separation medium and the support plate in the outer portion of the separation medium to bond the separation medium to the support plate.

20. A filter element mountable in a vibratory separation system, the filter element comprising:

a support plate;

a separation medium mounted on the support plate and having an inner portion, an intermediate portion and an outer portion;

a drainage layer disposed between the separation medium and the support plate in the intermediate portion of the separation medium; and

a bonding layer disposed between the separation medium and the support plate in the outer portion of the separation medium to bond the separation medium to the support plate.

21. A filter element mountable in a vibratory separation system, the filter element comprising:

a substantially flat support plate having first and second sides and one or more radially extending permeate passages;

a separation medium mounted on each side of the support plate; and

a drainage layer disposed between each separation medium and the support plate, wherein the drainage layer communicates with the permeate passages in the support plate.

22. The filter element of any one of claims 13-21, wherein the support plate has at least one through hole, and wherein the drainage layer has a cutout surrounding the through hole of the support plate, whereby the drainage layer is not present between the separation medium and the support plate in the vicinity of the through hole.

23. The filter element of any one of claims 13-22, wherein the support plate includes a central opening and at least one radially extending drainage slot, the drainage slot providing fluid communication between the drainage layer and the central opening.

24. A filter element mountable in a vibratory separation system, the filter element comprising:

a composite including

a support plate,

a separation medium, and

a drainage layer disposed between the support plate and separation medium;

wherein the composite is free of a bonding layer.

25. A membrane module comprising a plurality of stacked filter elements as in any of the preceding claims.

26. A vibratory separation system comprising:

a membrane module as in claim 25;

a drive mechanism coupled to the membrane module for imparting vibratory motion to the filter elements, thereby resisting fouling at the upstream surface of the permeable membranes;

a process fluid inlet communicating with the upstream surface of each permeable membrane; and

a permeate outlet communicating with the downstream surface of each permeable membrane.

27. A method of forming a filter element comprising:

forming a composite comprising a support plate having a plurality of through holes, a plurality of sealing members each disposed at one of the through holes, at least one separation medium disposed on a side of the support plate;

applying heat and pressure to the composite to soften the sealing members; and

cooling the composite to solidify the sealing members and form fluid-tight seals between the separation medium and a surface of the support plate at each of the through holes.

28. The method of claim 27, wherein forming the composite includes disposing a bonding layer between the separation medium and the support plate, the method further

comprising:

applying heat and pressure to the composite to soften the bonding layer; and

cooling the composite to adhere the bonding layer to the separation medium and the support plate.

29. The method of claim 27 or 28 further comprising applying heat and pressure to the composite to soften the sealing members to cause the sealing members to enter into and fill interstices in the bonding layer.

30. The method of claim 27, 28 or 29, wherein forming the composite includes disposing a drainage layer between the separation medium and the support plate.

31. The method of any one of claims 27-30, wherein the support plate has a second side, and wherein forming the composite includes disposing a second separation medium on the second side of the support plate.

32. The method of claim 31, wherein forming the composite includes disposing a second bonding layer between the second separation medium and the support plate.

33. The method of claim 32, wherein forming the composite includes disposing a second drainage layer between the second separation medium and the support plate.

34. A method of forming a filter element comprising:

forming a composite comprising a support plate having a plurality of through holes, a separation medium disposed on a side of the support plate, wherein each of the through holes contains a curable liquid material;

allowing the curable liquid material within each through hole to cure to form a fluid-tight seal between the separation medium and a surface of the support plate.

35. The method of claim 34 further comprising applying pressure to the composite while the curable liquid material is being cured.

36. The method of claim 34 or 35, wherein forming the composite includes disposing a bonding layer between the separation medium and the support plate.

37. The method of claim 36 further comprising:

applying heat to the composite to soften the bonding layer; and

cooling the composite to adhere the bonding layer to the separation medium and the support plate.

38. The method of claim 36 or 37 further comprising causing the curable liquid material within each through hole to enter into and fill interstices in the bonding layer.

39. The method of any one of claims 34-38 further comprising disposing a drainage layer between the separation medium and the support plate.

40. The method of any one of claims 34-39, wherein the support plate has a second side, and wherein forming the composite includes disposing a second separation medium on the second side of the support plate.

41. The method of claim 40, wherein forming the composite includes disposing a second bonding layer between the second separation medium and the support plate.

42. The method of claim 41, wherein forming the composite includes disposing a second drainage layer between the second separation medium and the support plate.

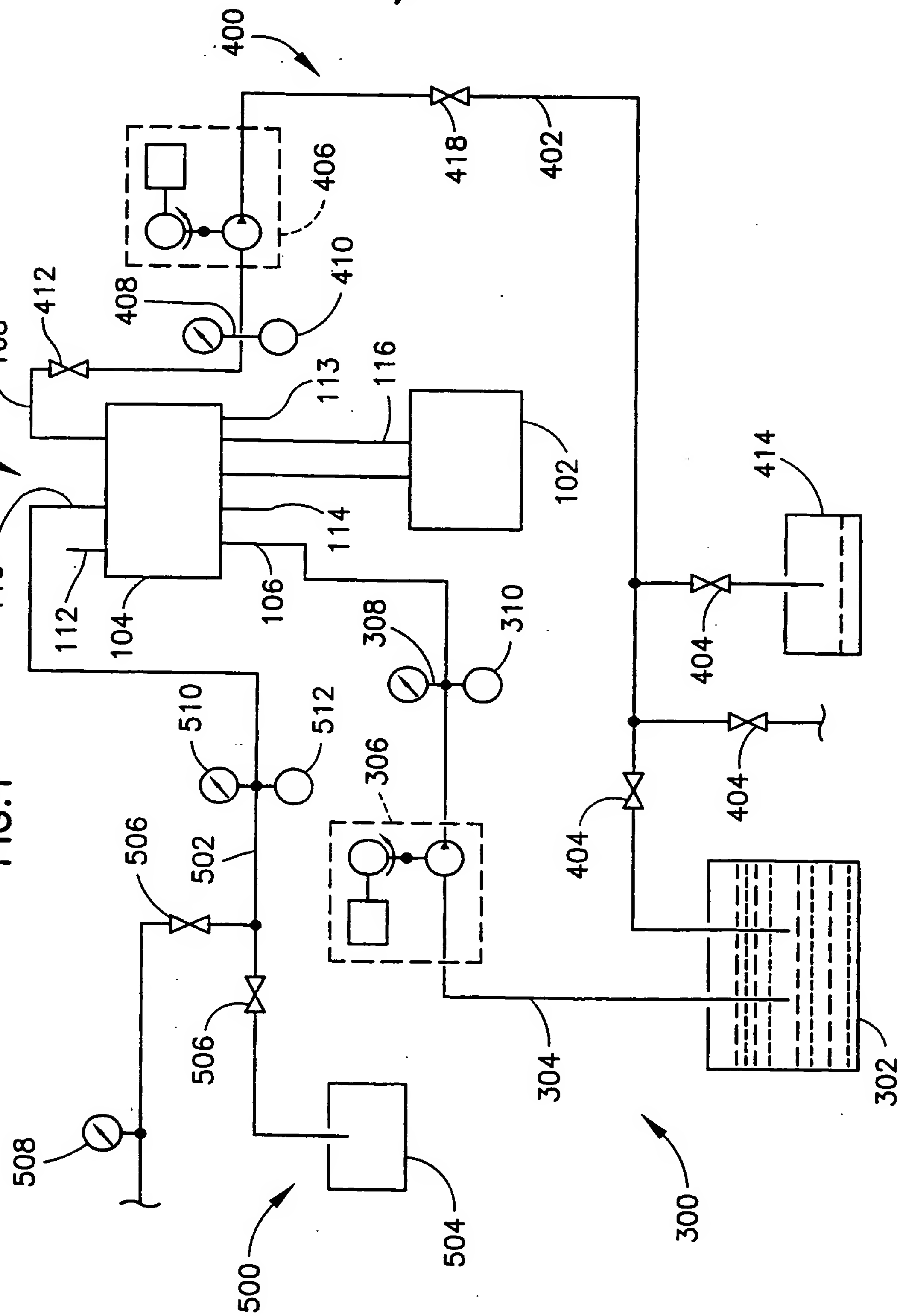
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FIG.1

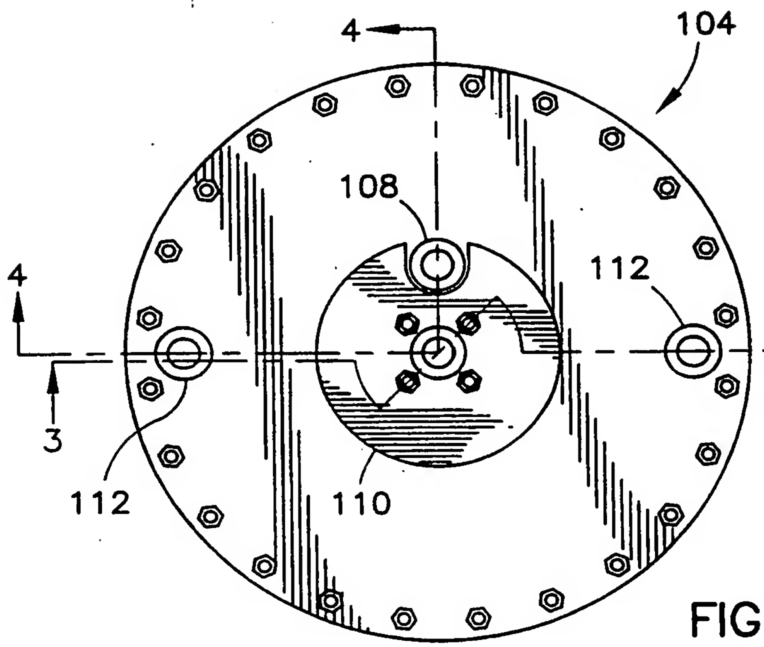
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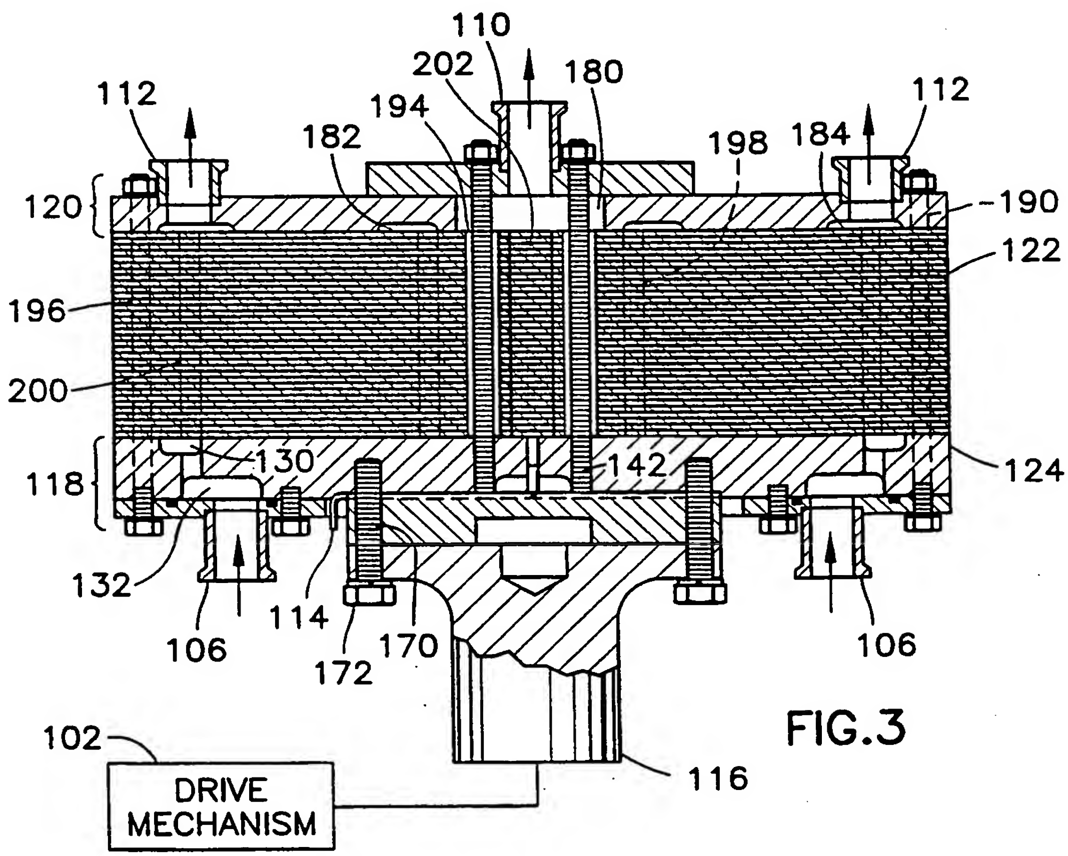
FIG.2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DRIVE MECHANISM
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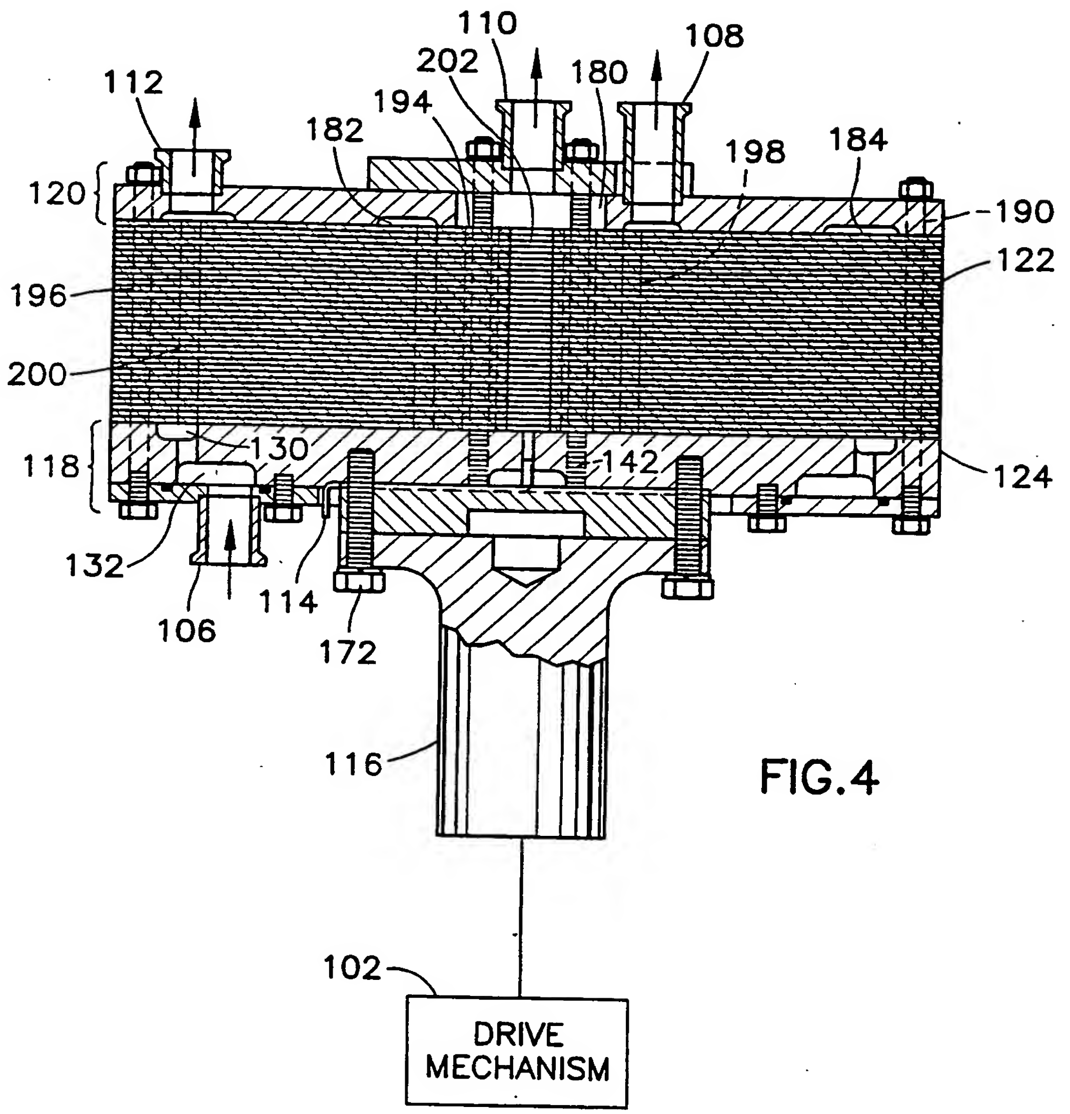
FIG.3



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DRIVE MECHANISM

FIG.4

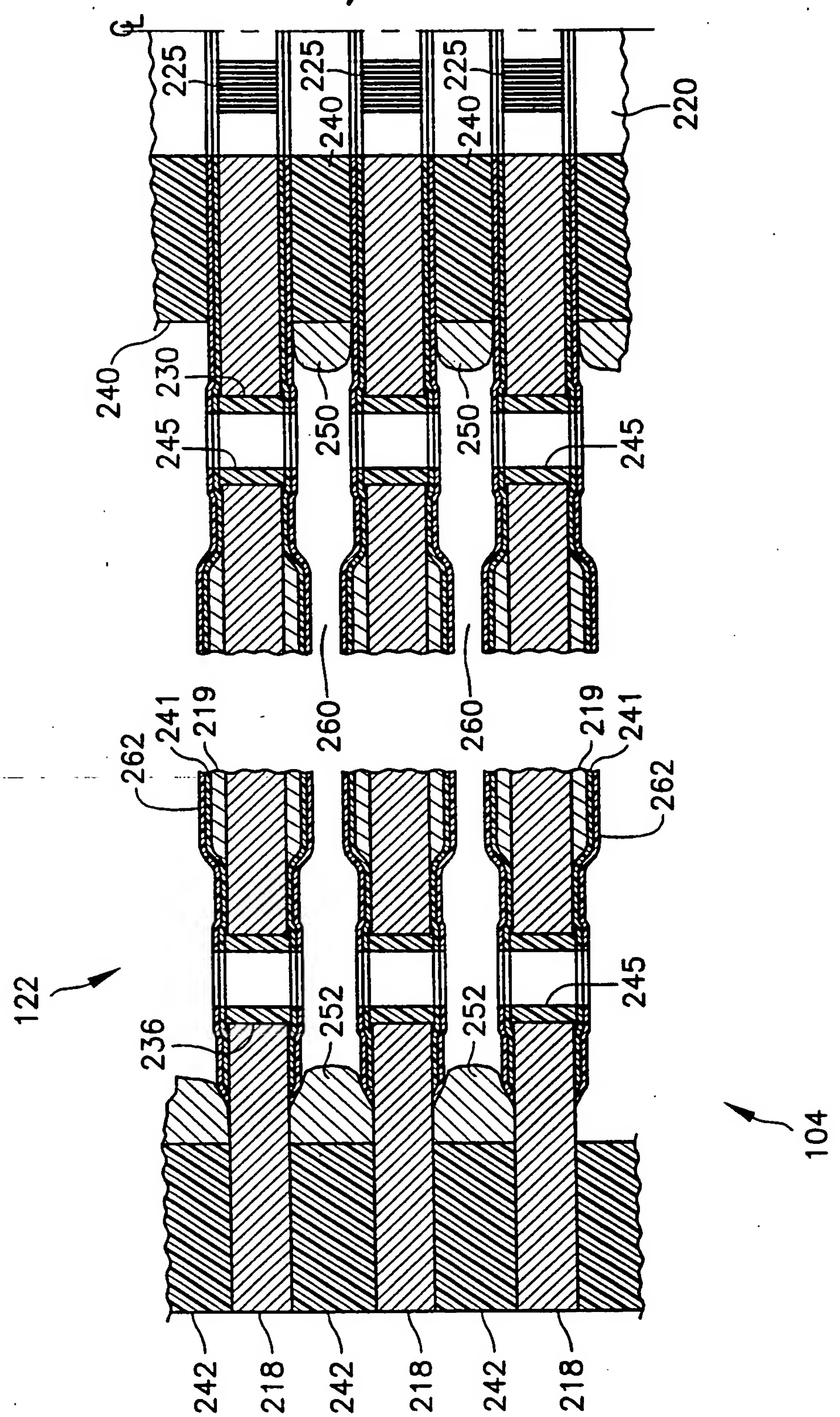


FIG.5

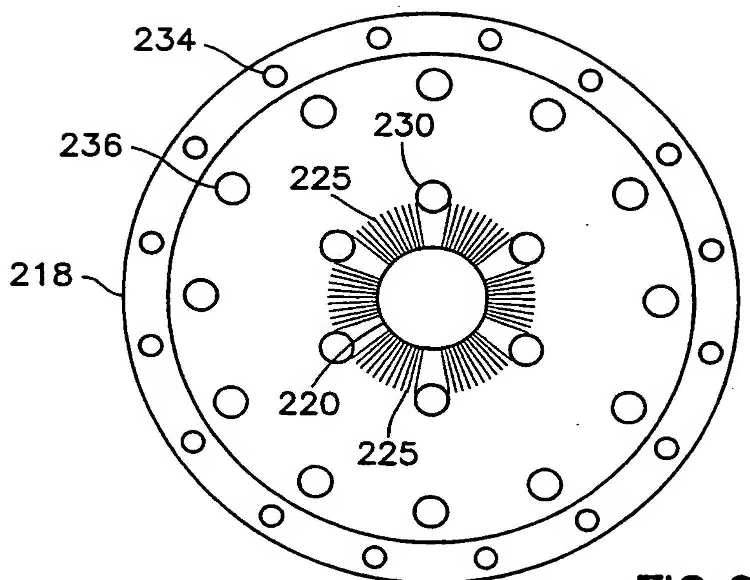
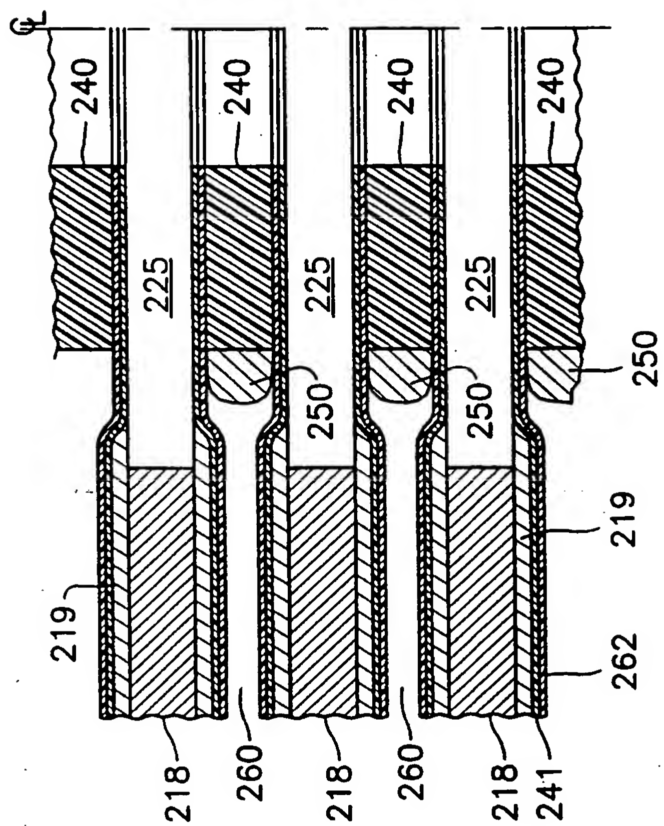


FIG.6

FIG.7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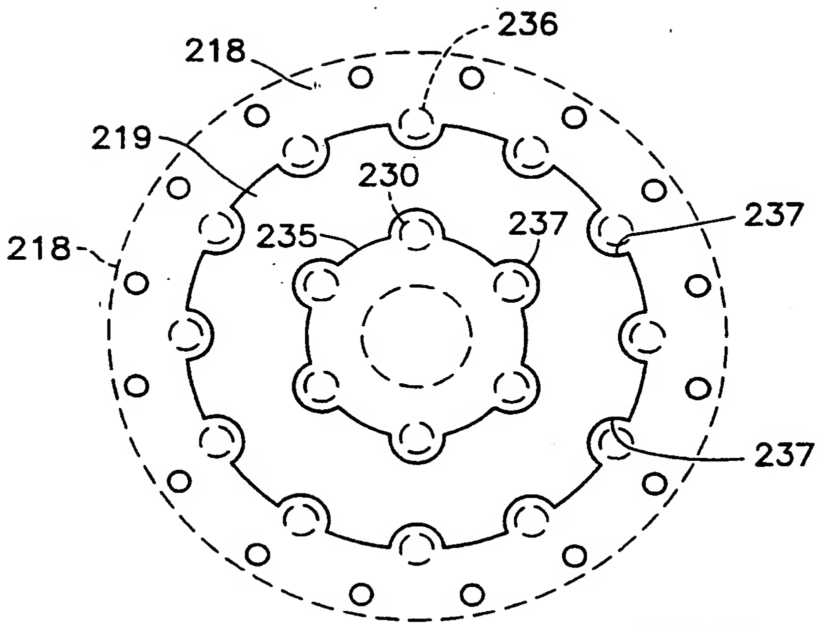


FIG.8

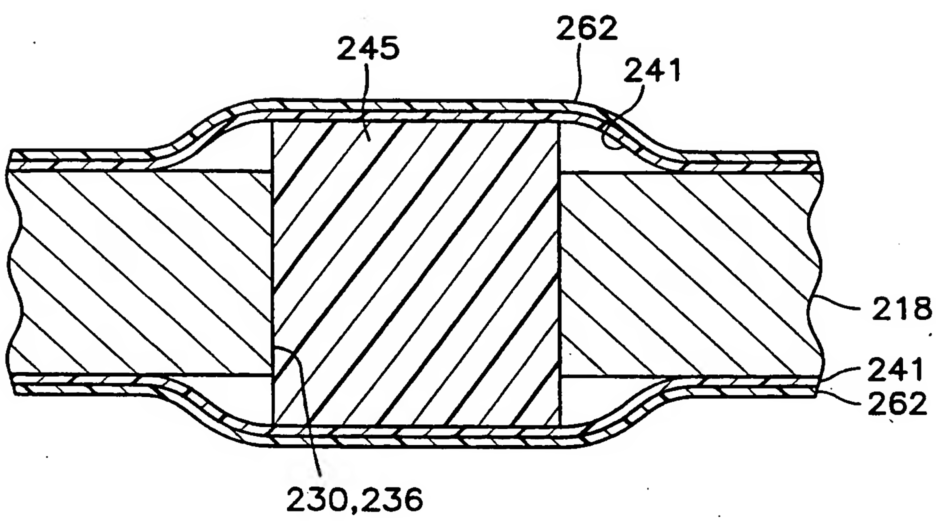


FIG.9

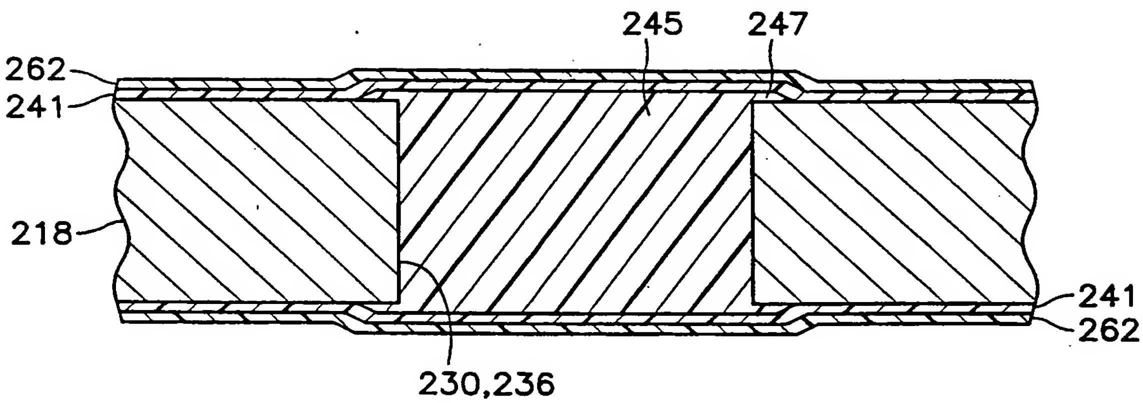


FIG.10

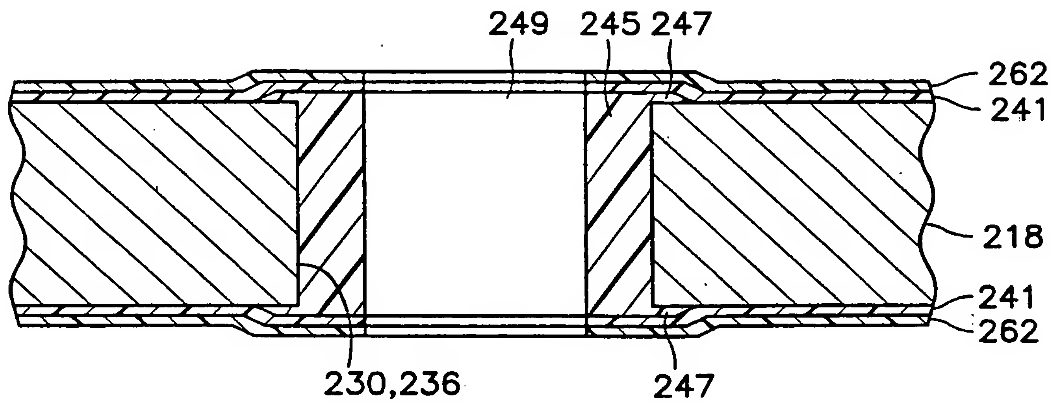
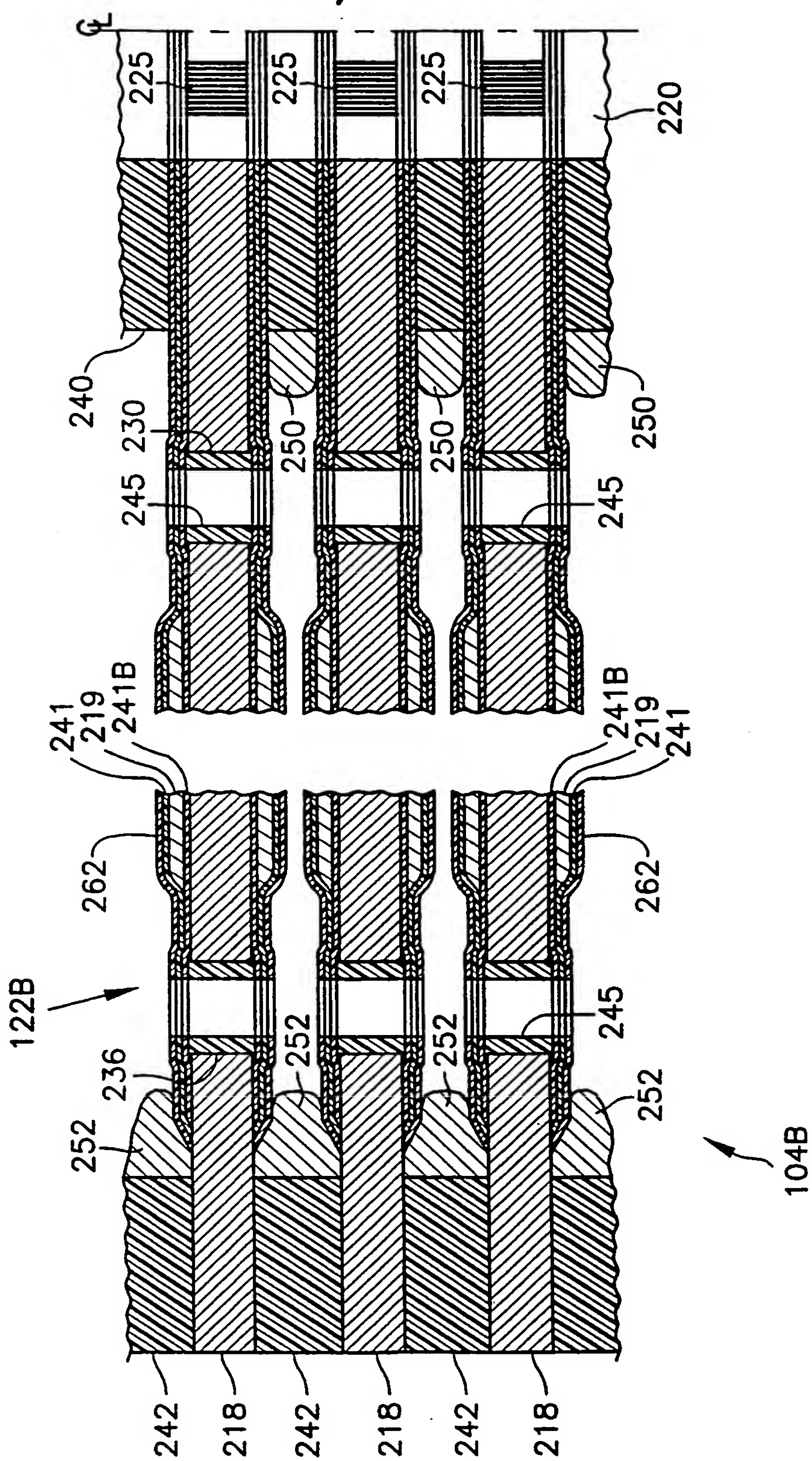


FIG.11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104B
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FIG.12

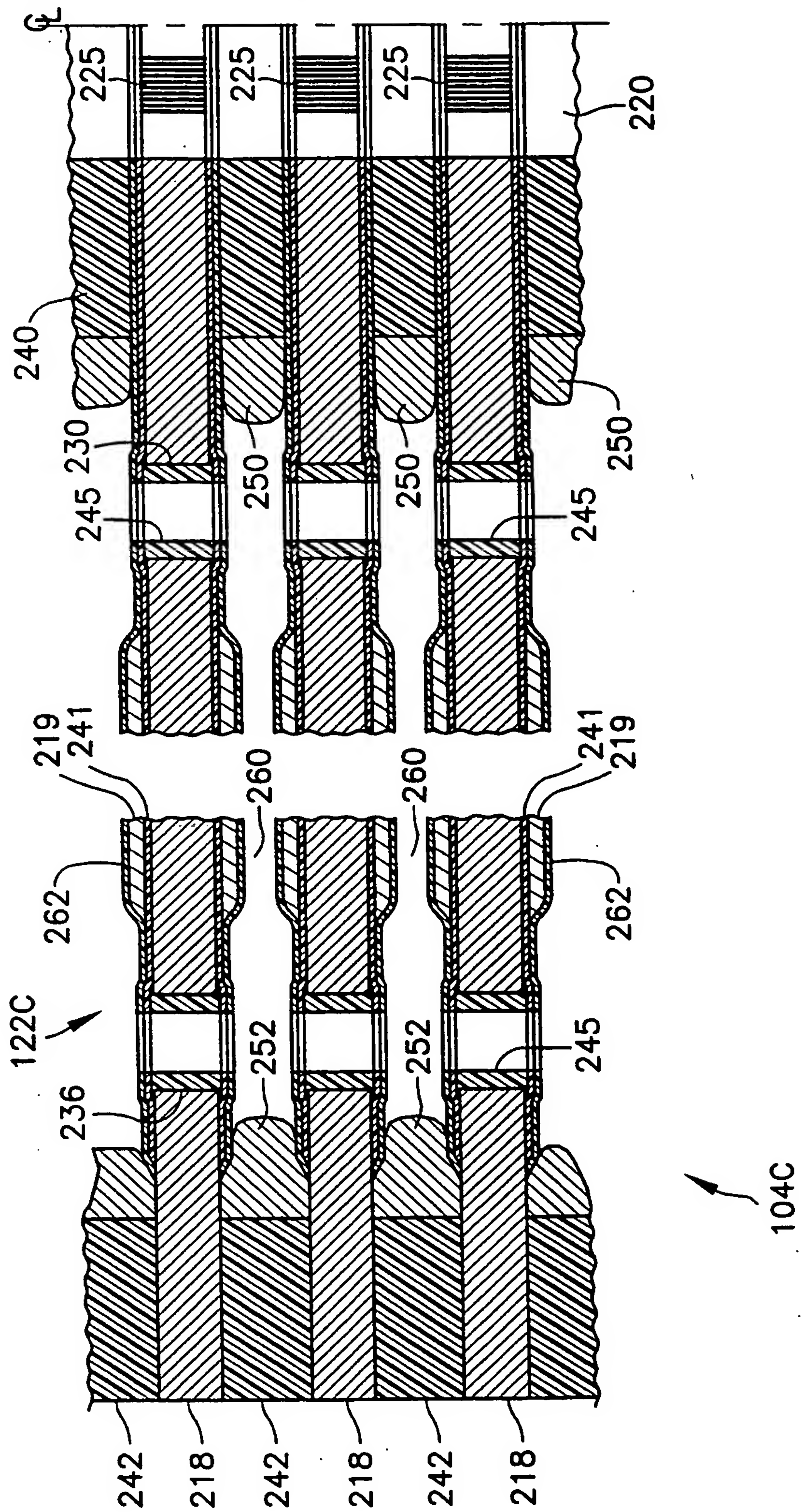
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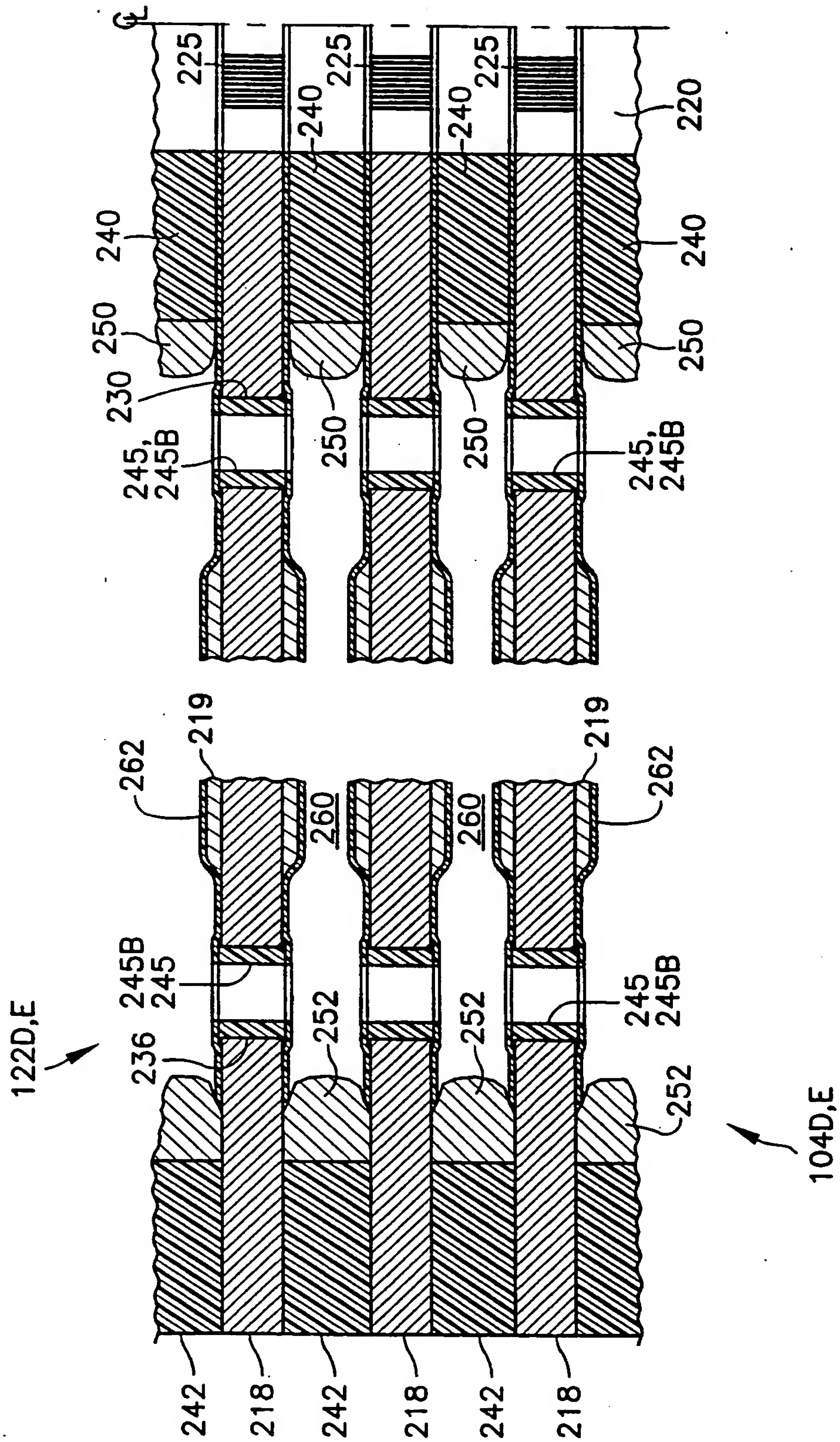
FIG.13

FIG.14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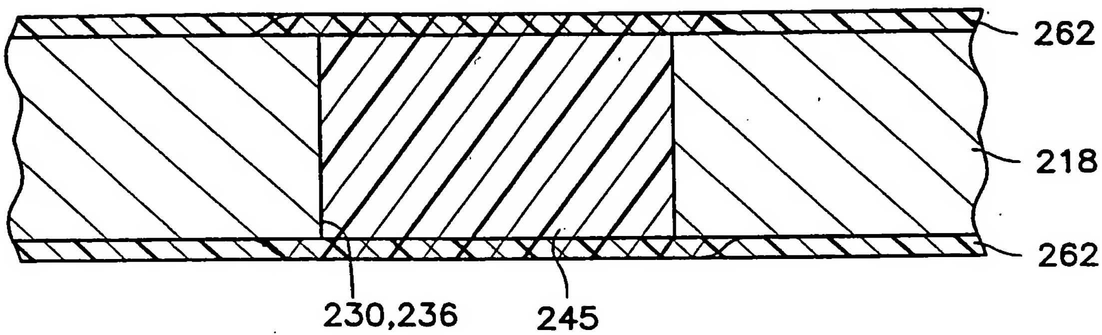

FIG.15

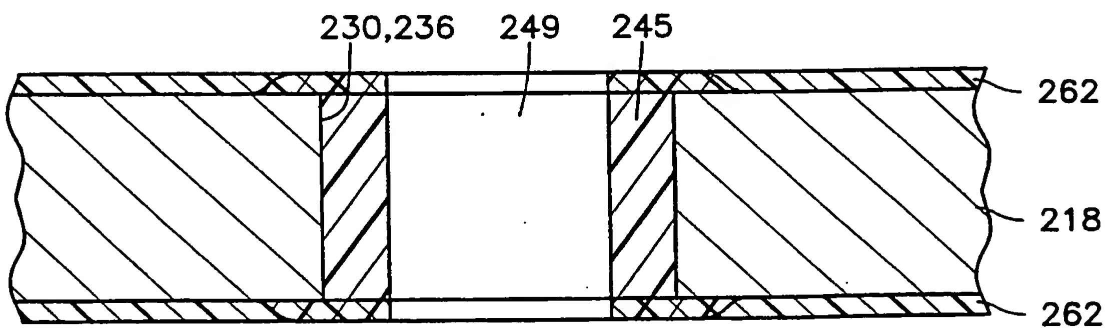

FIG.16

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